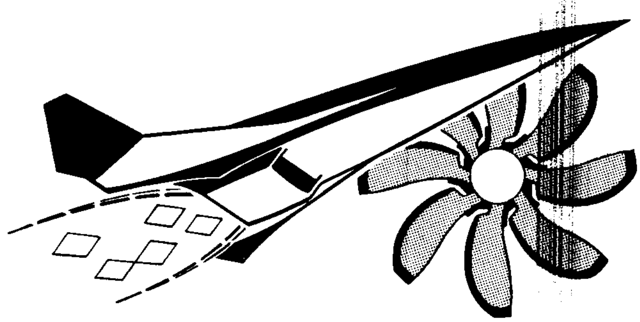
NASA Conference Publication 10003

Aeropropulsion '87

Session 2—
Aeropropulsion Structures Research



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Preprint for a conference at
NASA Lewis Research Center
Cleveland, Ohio, November 17–19, 1987

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NASA
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CONTENTS

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AEROPROPULSION STRUCTURES

Lester D. Nichols

Aeropropulsion systems present unique problems to the structural engineer. The extremes in operating temperatures, rotational effects, and behaviors of advanced material systems combine into complexities that require advances in many scientific disciplines involved in structural analysis and design procedures. This presentation provides an overview of the complexities of aeropropulsion structures and the theoretical, computational, and experimental research conducted to achieve the needed advances.

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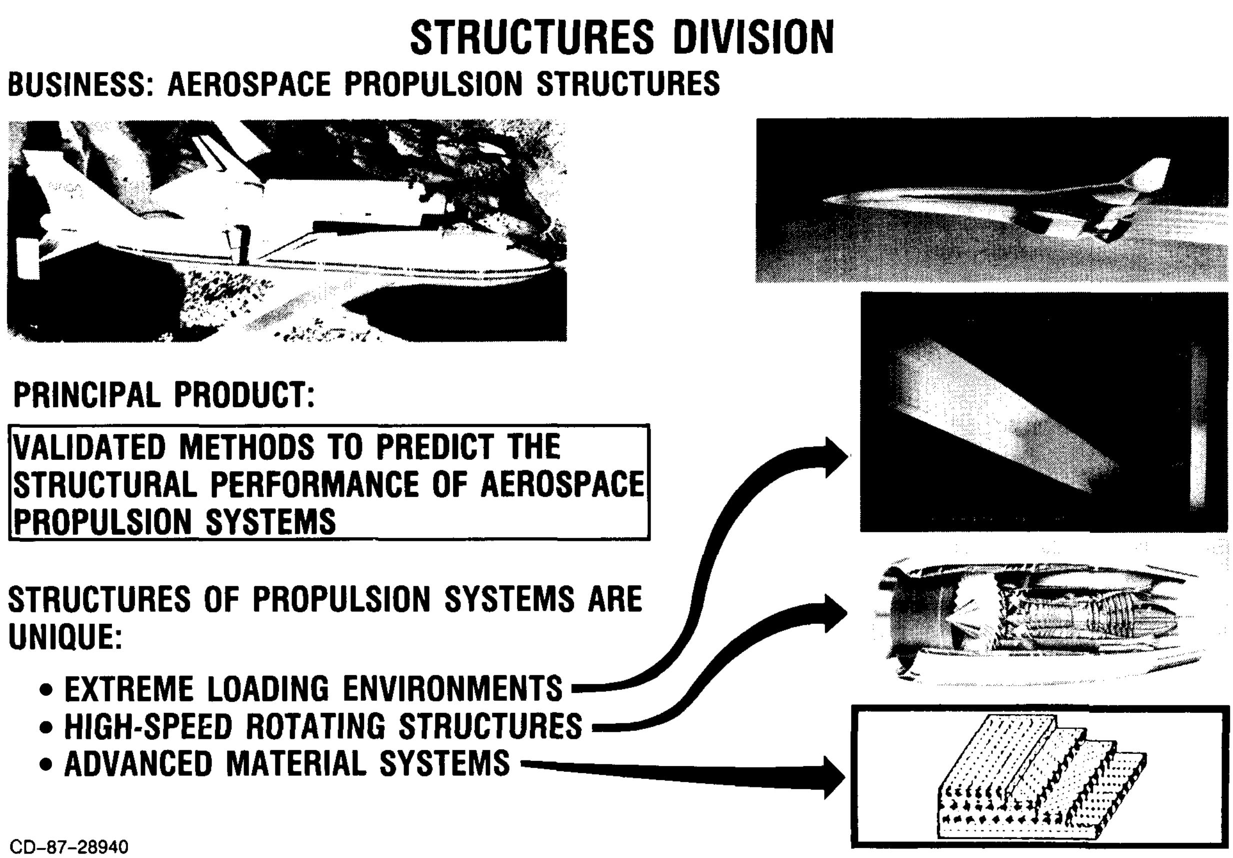
STRUCTURES DIVISION

The Structures Division is engaged principally in developing validated analysis methods for predicting the performance of the structural components and systems of aerospace propulsion machinery. Performance here refers to a diversity of operating behavior characteristics, such as instantaneous or time-dependent stresses and deformations, structural dynamics, aeroelasticity, material behavior, and structural-life-related phenomena. Experiments are used both to validate methods and to understand complex structural and material behaviors in order to develop theoretical models that emulate them.

The structures of aeronautical propulsion systems have a unique combination of complexities: they operate with long life in extremely harsh loading environments, have rotating components with complex dynamic behavior, and are constructed of lightweight advanced material systems with unique characteristics.



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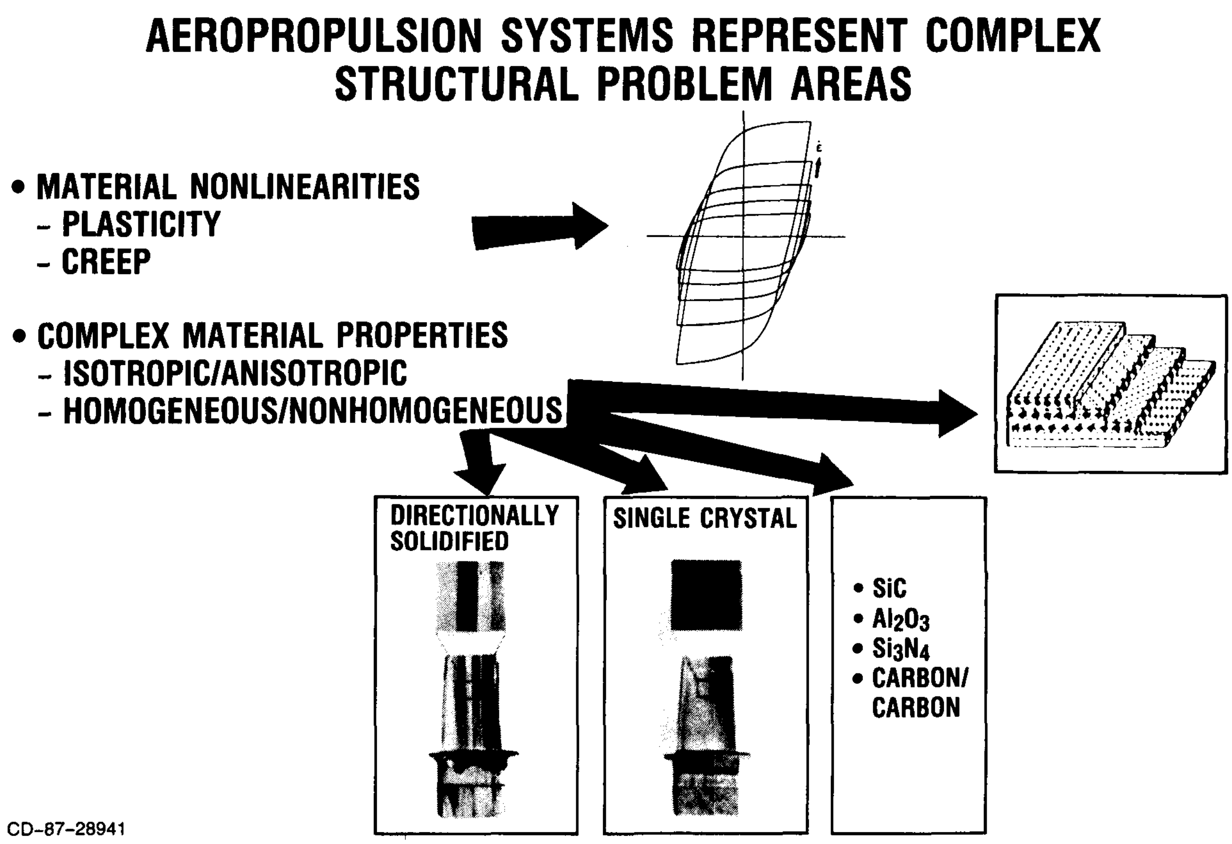
AEROPROPULSION SYSTEMS REPRESENT COMPLEX STRUCTURAL PROBLEM AREAS

Propulsion systems present a number of complex structural problems from different sources. Because of the loading environment materials exhibit two forms of nonlinear behavior: plasticity (considered to be instantaneous response), and creep (deformation and stress relaxation accumulating with time). Advanced material systems, because of their microstructures, represent local complexities that have to be included in global analysis methods. Single-crystal, directionally solidified, or fiber-reinforced materials result in anisotropic and nonhomogeneous local structures that must be mathematically characterized over wide ranges of nonlinear response and over the predicted structure life.



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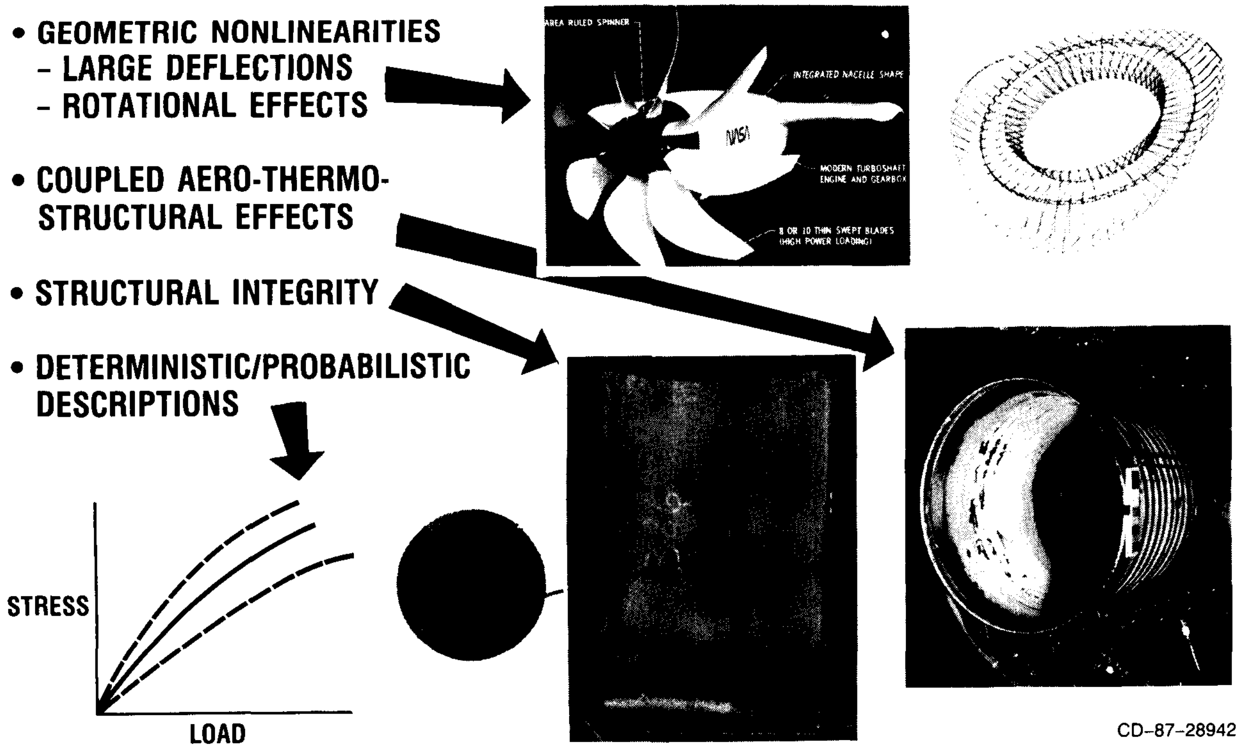
Another source of complexity is the large deflection associated with flexible structures, usually coupled with aerodynamic and thermal effects. Furthermore descriptions of the loading environments and the material properties may not be available except in the form of a probability distribution. Phenomena related to structural integrity and life are among the most vexing and most important considerations. All these complexities and their possible interactions have to be considered in developing credible methods for predicting the structural behavior of propulsion systems.

AEROPROPULSION SYSTEMS REPRESENT COMPLEX STRUCTURAL PROBLEM AREAS (concl'd)



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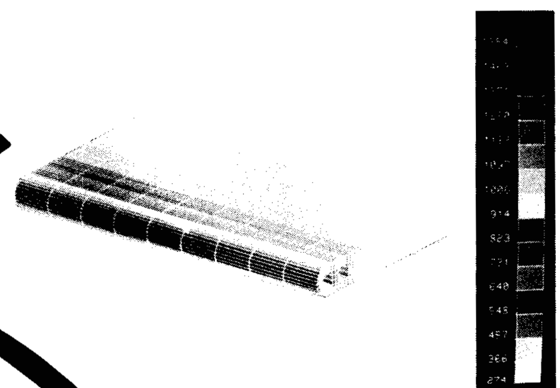
PARTICIPATING DISCIPLINES

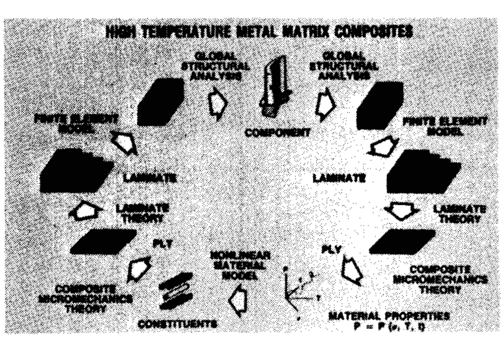
Research is needed in a number of scientific disciplines to solve the complex problems facing the structural designer of aeropropulsion systems. The nonlinearities of material behavior require major advances over conventional finite element or boundary element methods. These advances also have to reflect the new opportunities offered by the upcoming multiprocessor computer revolution.

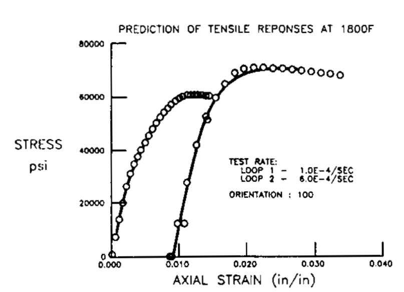
Shortcomings in characterizing the material behavior under cyclic thermomechanical mission loads are major obstacles to improved accuracy and computational efficiency. Combining the required advances in constitutive modeling with the mechanics of fiber-reinforced composites compounds the complexity.

PARTICIPATING DISCIPLINES

- **ADVANCED ANALYSIS METHODS**
  - **FINITE ELEMENT METHODS**
  - **BOUNDARY ELEMENT METHODS**
- **MATERIAL BEHAVIOR MODELING**
  - **CONSTITUTIVE MODELING**
  - **MECHANICS OF COMPOSITES**







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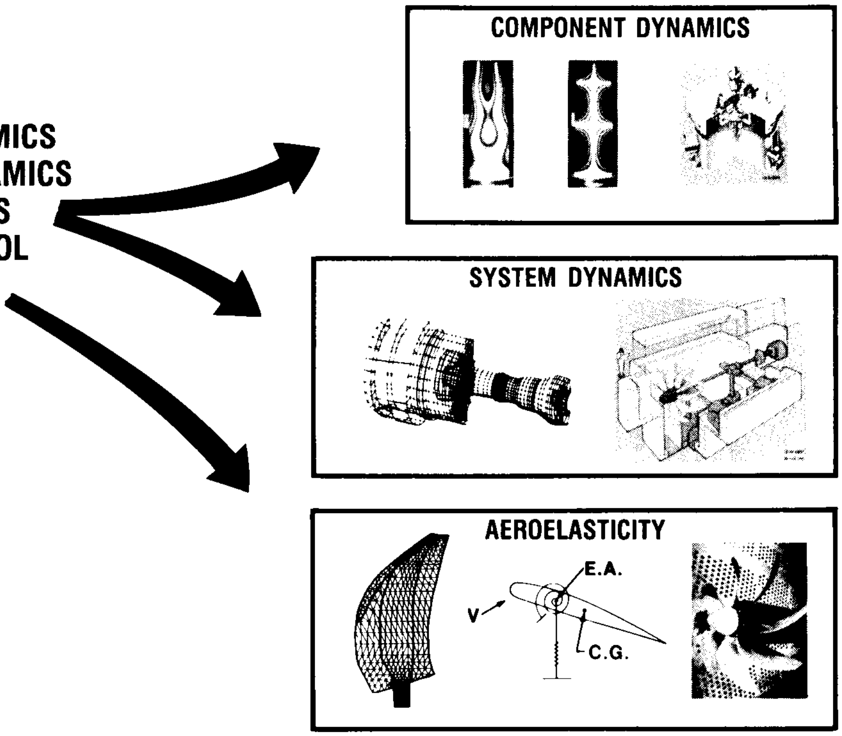
PARTICIPATING DISCIPLINES (cont'd)

Nonlinear dynamics and aeroelasticity are needed to predict the operating characteristics of rotating, flexible bladed systems so that acceptable operating envelopes can be defined.

PARTICIPATING DISCIPLINES (cont'd)

- **STRUCTURAL DYNAMICS**
  - COMPONENT DYNAMICS
  - SYSTEM DYNAMICS
  - VIBRATION CONTROL
  - AEROELASTICITY



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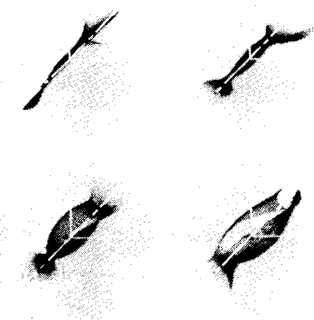
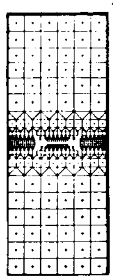
PARTICIPATING DISCIPLINES (cont'd)

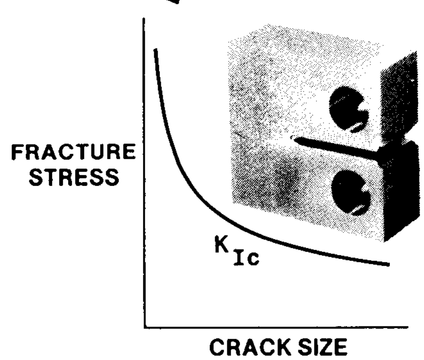
Methods for predicting various structural-integrity-related behaviors of advanced material systems are needed in order to realize future aeropropulsion concepts with their demands for lighter structures operating in extremely hostile environments.

PARTICIPATING DISCIPLINES (cont'd)

- STRUCTURAL INTEGRITY PREDICTION
  - STRENGTH
  - STATIC AND DYNAMIC STABILITY
  - THERMOMECHANICAL FATIGUE AND FRACTURE
  - COMPOSITES PHENOMENA







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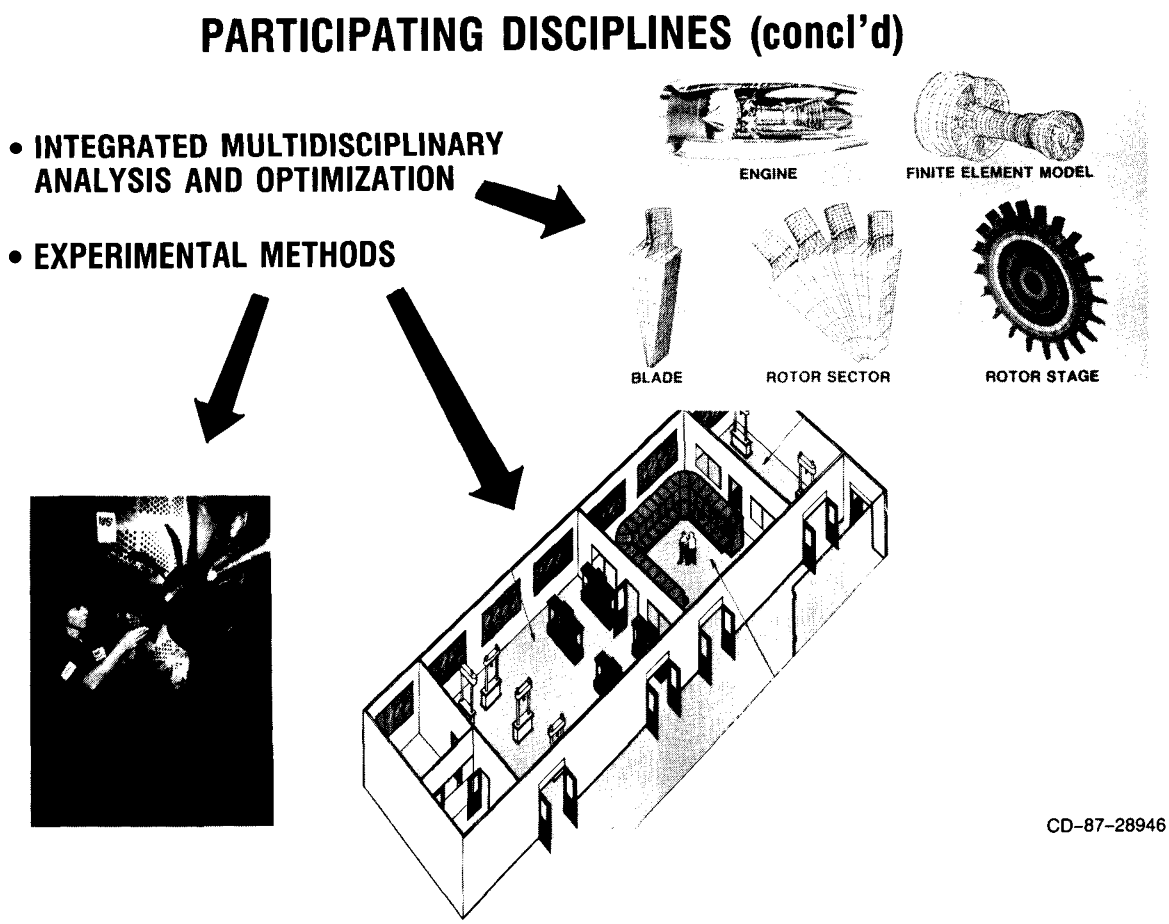
PARTICIPATING DISCIPLINES (concl'd)

The final intent of the structural designer is not just to analyze trial design concepts, but also to approach an optimum design. Multidisciplinary design optimization methods are needed to guide the human designer through the complex interactions of the design variables toward an optimum design. Experimental capabilities are needed in dynamics and in high temperatures to study new phenomena and to validate theoretical models.



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STRUCTURES WORK ELEMENTS

The three fundamental structures work areas are structural mechanics, structural dynamics, and life prediction methods. The structural mechanics work is focused on the mechanics of materials in order to develop models for their behavior under cyclic thermomechanical mission load conditions. These models are needed in the advanced integrated structural analysis methods being developed.

Under structural dynamics the aeroelasticity of flexible, rotating bladed systems is important for advanced propulsion design concepts. Developments in vibration control and systems dynamics are needed to ensure safe and efficient operation of rotating propulsion structures, particularly as they become lighter and operate at higher speeds.

The life prediction focus is on understanding, predicting, and controlling structural failures caused by fatigue and fracture. A wide range of advanced materials and material systems is being considered, many of them more brittle and therefore less forgiving.

STRUCTURES WORK ELEMENTS

STRUCTURAL PERFORMANCE

- CONSTITUTIVE RELATIONSHIPS MODELING AND EXPERIMENTS
- MECHANICS OF COMPOSITES
- VIBRATION CONTROL
- SYSTEM DYNAMICS
- AEROELASTICITY

STRUCTURAL LIFE PREDICTION

- INTERACTIVE EFFECTS ON FATIGUE LIFE
- DAMAGE INITIATION MODELING
- CRACK GROWTH
- MECHANICS OF FRACTURE

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STRUCTURES WORK ELEMENTS (concl'd)

The structural designer needs input data from all disciplines in the interdisciplinary chain of activities during product design. Advanced computational mechanics analysis methods are being developed for cyclic thermomechanical mission loads. Under computational methods the program architectures and algorithms are being developed that best utilize advances in computer technology. Mission load environments and also the properties of advanced material systems can often be best described in probabilistic terms. This provides designers with more information on which to base designs. Integrated analysis methods are coupled with optimization methods for integrated multidisciplinary design optimization. Experimental methods are needed for two purposes: to study and understand phenomena and formulate models, and to test models for validation. The capabilities developed are distributed to users and are also employed in providing consultation to and participation in major NASA projects.

STRUCTURES WORK ELEMENTS (concl'd)

INTEGRATED ANALYSIS AND APPLICATIONS

- COMPUTATIONAL MECHANICS
- COMPUTATIONAL METHODS
- PROBABILISTIC METHODS
- OPTIMIZATION AND TAILORING
- NONDESTRUCTIVE EVALUATION
- CONCEPT EVALUATION

PROJECT SUPPORT AND CONSULTATION

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DETERMINING STRUCTURAL PERFORMANCE

Michael A. Ernst
and
Louis J. Kiraly

ABSTRACT

The objective of this presentation is give an overview of the methods and concepts developed to enhance and predict structural dynamic characteristics of advanced aeropropulsion systems. Aeroelasticity, Vibration Control, Dynamic Systems, and Computational Structural Methods are four disciplines that make up the structural dynamic effort here at Lewis. The Aeroelasticity program develops analytical and experimental methods for minimizing flutter and forced vibration of aerospace propulsion systems. Both frequency domain and time domain methods have been developed for applications on the turbofan, turbopump, and advanced turboprop. In order to improve life and performance, the Vibration Control program conceives, analyzes, develops, and demonstrates new methods to control vibrations in aerospace systems. Active and passive vibration control is accomplished with electromagnetic dampers, magnetic bearings, and piezoelectric crystals to control rotor vibrations. The Dynamic Systems program analyzes and verifies the dynamics of interacting systems, as well as develops concepts and methods for high-temperature dynamic seals. Work in this field involves the analysis and parametric identification of large, nonlinear, damped, stochastic systems. The Computational Structural Methods program exploits modern computer science to fundamentally improve the usage of computers in the solutions of structural problems. Overall, the structural dynamic methods and concepts presented have greatly enhanced the performance and life of advanced aeropropulsion systems.

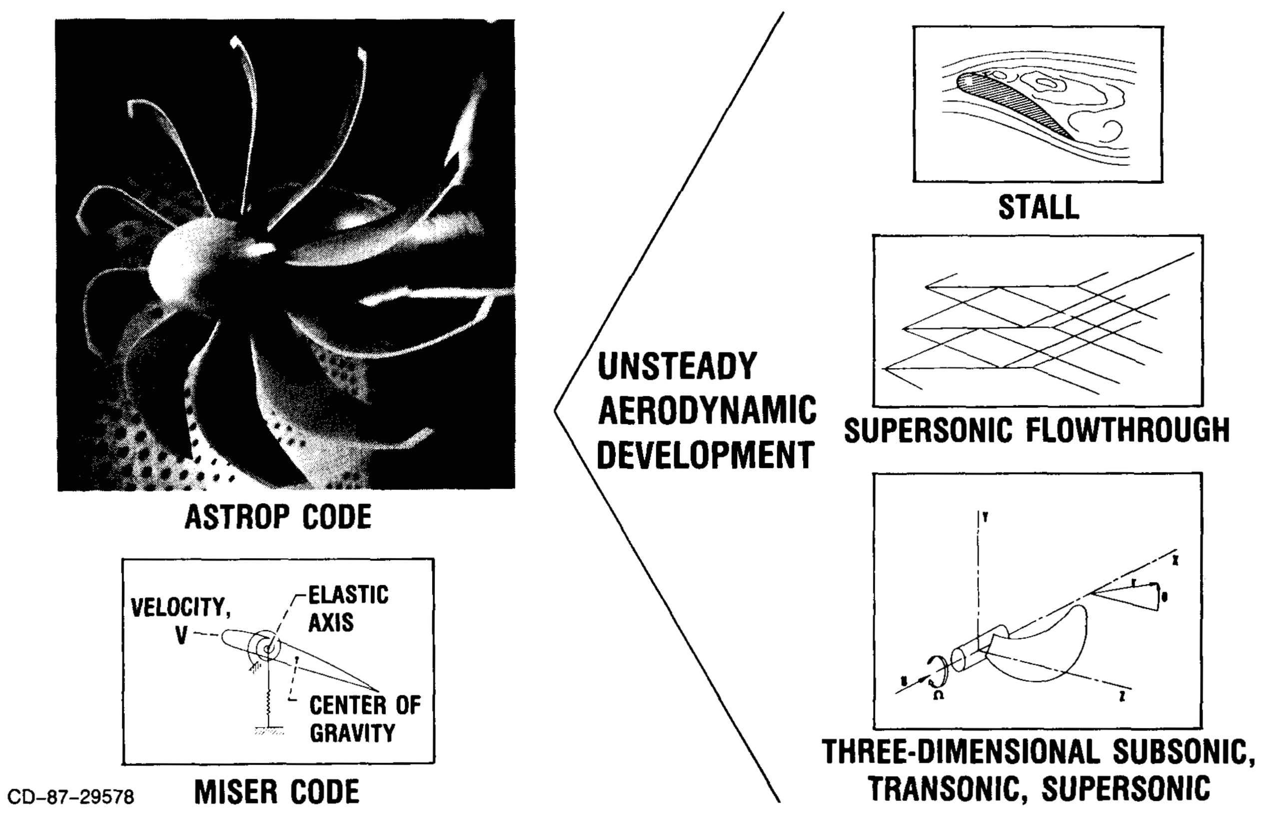
AEROELASTIC METHODS

The computer program MISER (mistuned engine response) is a two-dimensional aeroelastic program that allows the user to explore the effects of mistuning on a series of blade cross sections in cascade. The computer program ASTROP (aeroelastic stability and response of propulsion systems) is a three-dimensional program that allows the user to predict the aeroelastic nature of propfan blades in cascades. Both programs have the capability of analyzing blades in both the subsonic and supersonic (subsonic leading-edge locus) flow regimes.

In order to improve the capability of both MISER and ASTROP, work is in progress to extend the unsteady aerodynamic packages in both programs. For instance, work is currently in progress to extend ASTROP into the stall and transonic flow regimes, and MISER's unsteady aerodynamic package is being extended to handle supersonic axial flowthrough applications.

Over the past five years, both ASTROP and MISER have offered extensive insight into the aeroelastic behavior of propfans, as well as fan stages of turbofan engines.

AEROELASTIC METHODS

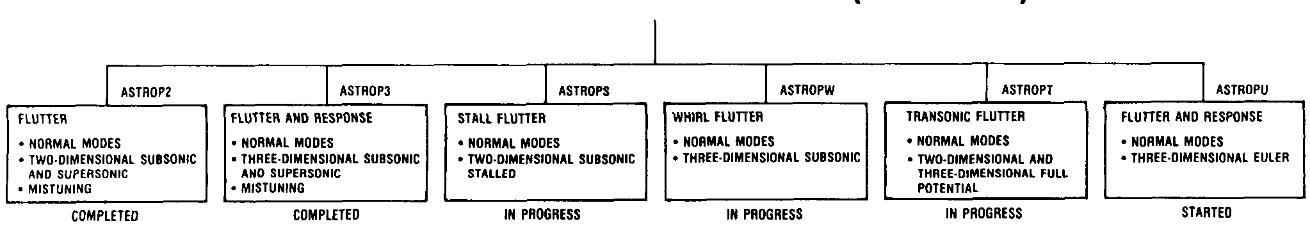


AEROELASTIC STABILITY AND RESPONSE OF PROPULSION SYSTEMS (ASTROP)

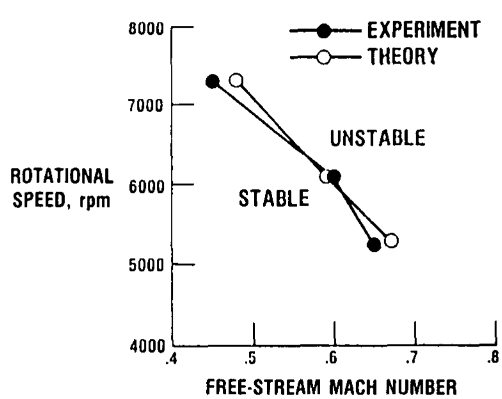
The turbomachinery aeroelastic effort at NASA Lewis Research Center includes unstalled and stalled flutter, forced response, and whirl flutter of propulsion systems. Even though the effort is currently focused on single-rotation and counterrotation propfans, the analytical models and the computer codes are applicable to turbofans with and without blade sweep and compressors. Because of certain unique features of propfans, it is not possible to directly use the existing aeroelastic technology of conventional propellers, turbofans, or helicopters. Therefore, reliable aeroelastic stability and response analysis methods for these propulsion systems must be developed. The development of these methods for propfans requires specific basic technology disciplines, such as two-dimensional and three-dimensional, steady and unsteady (unstalled and stalled), aerodynamic theories in subsonic, transonic, and supersonic flow regimes; modeling of composite blades; geometric nonlinear effects; and passive or active control of flutter and response. These methods for propfans are incorporated in the computer program ASTROP. The program has flexibility such that new and future models in basic disciplines can be easily implemented.

The ASTROP3 code predicted flutter boundary of the SR3C-X2 (eight-bladed composite propfan wind tunnel model) is compared with the measured one. The comparison shows a very good agreement between theory and experiment. More details on the ASTROP code and further code validatory results can be found in NASA TM-88944 and NASA TM-88959.

AEROELASTIC STABILITY AND RESPONSE OF PROPULSION SYSTEMS (ASTROP)



COMPARISON OF EXPERIMENTAL AND THEORETICAL FLUTTER BOUNDARY



PROPFAN WIND TUNNEL MODEL

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BLADE VIBRATION CONTROL

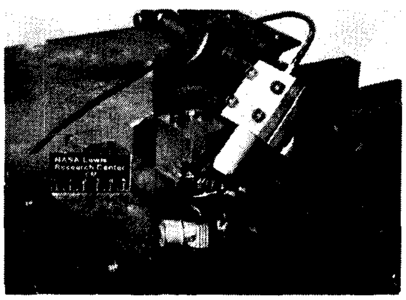
Shown in the figure are examples of projects in passive control of blade vibration. The variable-normal-load friction-damper test fixture was developed to allow detailed study of friction dampers in a rotating environment. The data generated with this test fixture were used to fine tune and verify advanced mathematical models of friction damper behavior. The models were used to show that friction dampers have the potential to stabilize fluttering fan blades.

The first-stage turbine blades of the space shuttle main engine (SSME) high-pressure oxygen pump (HPOTP) have experienced cracking problems due to excessive vibration. A solution is to incorporate a well-designed friction damper to attenuate blade vibration. An integrated experimental-analytical approach was used to evaluate a damper design. An optimized design resulted in a modest microslip damper.

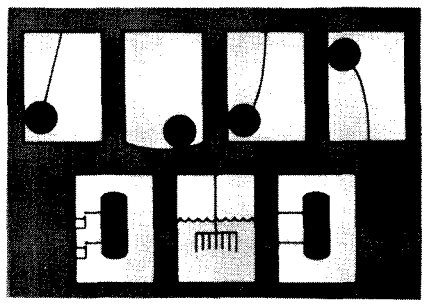
An analytical study of impact dampers has been completed. The model predicts that a relatively light impactor (1 to 4 percent of the blade mass) produces substantial damping. In addition, the phenomenon of frequency tuning is not present for the impact damper. However, it is replaced by what might be called amplitude tuning. Experimental verification is now being planned.

BLADE VIBRATION CONTROL

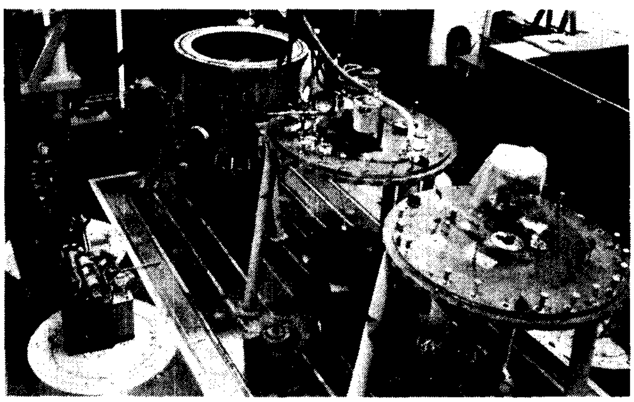
VARIABLE-NORMAL-LOAD FRICTION DAMPER



SSME HIGH-PRESSURE OXYGEN PUMP (HPOTP) FRICTION DAMPER



ADVANCED CONCEPT IMPACT DAMPERS



SPIN RIG VERIFICATION

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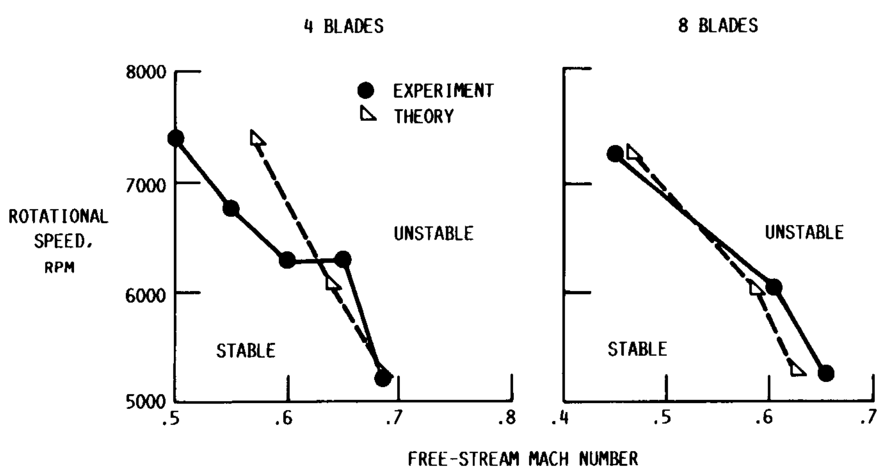
PROPFAN AEROELASTIC RESEARCH

An experimental and analytical research program is being conducted to understand the flutter and forced response characteristics of advanced high-speed propellers or propfans. The aeroelastic analysis for the design of propfans is more complex than for conventional propellers because blade characteristics and aerodynamic operating conditions are different for propfans. Propfans have six or more swept, thin, low-aspect-ratio blades, and the blades operate in subsonic, transonic, and possibly supersonic flows. Flutter and forced response data have been obtained from 2-ft-diameter single-rotation and counterrotation models in NASA and industry wind tunnels. The large-scale demonstrator propfans that have been flight tested during 1986 and 1987 were designed with analyses that were developed and verified with data from this program.

A comparison of measured and calculated flutter boundaries for a propfan model, called SR3C-X2, is shown in the figure. The theoretical results, from the Lewis-developed ASTROP3 analysis, include the effects of centrifugal loads and steady-state, three-dimensional airloads. The analysis does reasonably well in predicting the flutter speeds and slopes of the boundaries. However, the difference between the calculated and measured flutter Mach numbers is greater for four blades than for eight blades. This implies that the theory is overcorrecting for the decrease in the aerodynamic cascade effect with four blades.

COMPARISON OF MEASURED AND CALCULATED FLUTTER BOUNDARIES
SR3C-X2 PROPFAN MODEL



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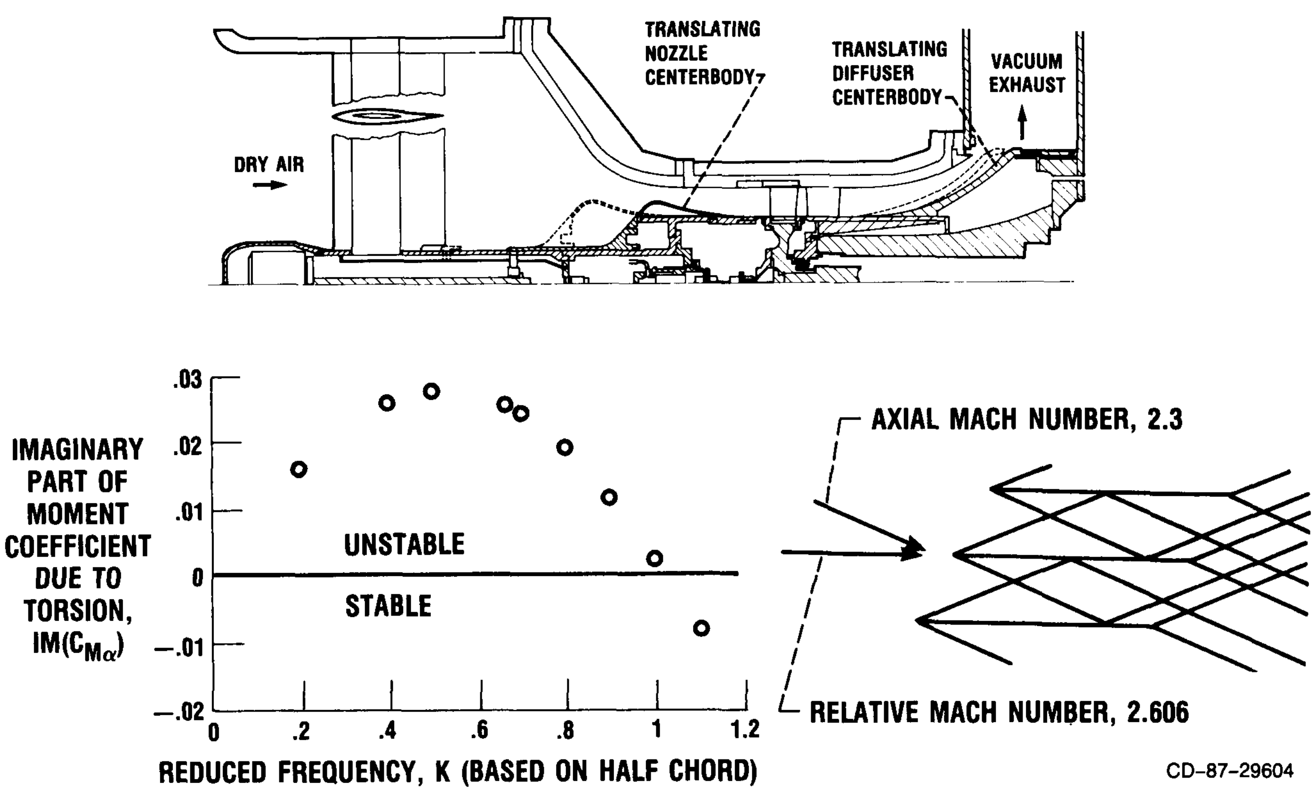
SUPERSONIC AXIAL THROUGHFLOW

Recent interest in supersonic and hypersonic flight has renewed interest in developing propulsion systems which include a supersonic axial-flow fan. As a result, an effort is in progress at NASA Lewis Research Center to build a single-stage, supersonic axial-flow fan.

Conventional fans or compressors normally only encounter supersonic flow relative to the blades, or when subject to supersonic flow normal to the plane of blade rotation, decelerate the flow through shocks which are contained upstream of the locus of blade leading edges. The supersonic axial-flow fan encounters supersonic flow normal to the plane of rotation as well as relative to the blades, and has supersonic flow through the entire blade passage. This fan is characterized by oblique shocks contained downstream of the locus of blade leading edges.

Since the aeroelastic stability of the proposed single-stage fan was a concern, an analytical capability was needed to predict the unsteady aerodynamic loading. Consequently, a computer program was developed by John K. Ramsey, using Lane's equation for the unsteady pressure distribution, for the case of supersonic axial flow. This code (Lane's code) predicts the unsteady pressure distribution for a cascade or isolated airfoil in supersonic axial flow. This code can be connected to any aeroelastic code.

SUPERSONIC AXIAL THROUGHFLOW



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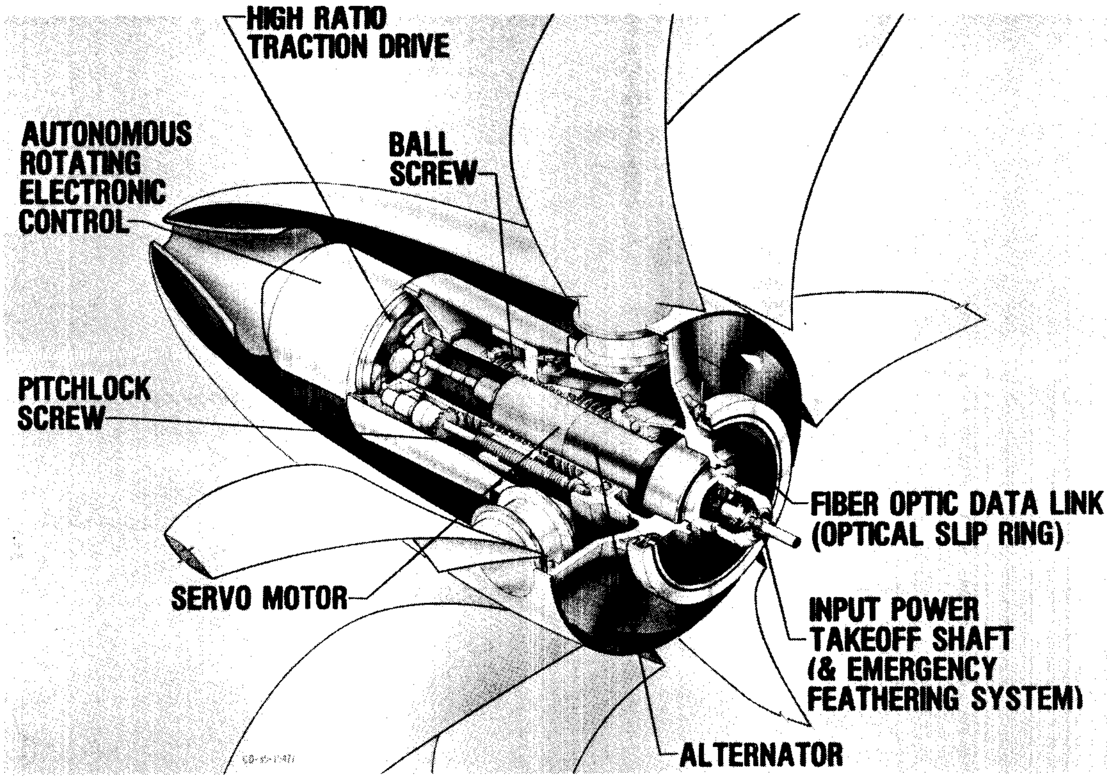
NASA Lewis, in conjunction with General Electric Company, developed a high-precision servomechanism for controlling turboprop aircraft blade angles. The pitch-change mechanism can accurately control the variable pitch of large (13 000 hp) turboprop aircraft propellers over the complete spectrum of flight operating conditions and helps attain advanced turboprop performance goals of improving propulsion system efficiency by 30 percent and reducing operating costs by 10 percent.

Advanced design features include a fiber-optic data link, a high-speed electric motor/alternator combination, a high-mechanical-ratio blade articulating mechanism, and an autonomous propeller that generates its own electrical power and has an independent self-contained control module.

The key to minimizing noise with these large propeller systems is accurate synchrophasing (or precise blade speed and phase synchronization of left and right propellers). The blade angle resolution capabilities of this pitch-control mechanism have been theoretically shown to meet or exceed the requirements for minimizing blade noise experienced by passengers onboard aircraft expected to be flying in the 1990's.

ADVANCED TURBOPROP PITCH-CHANGE MECHANISM



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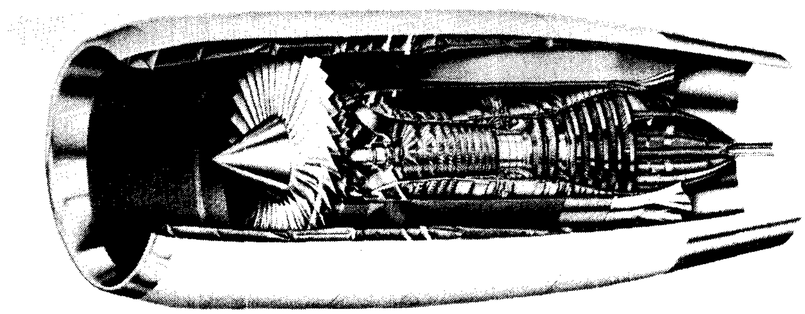
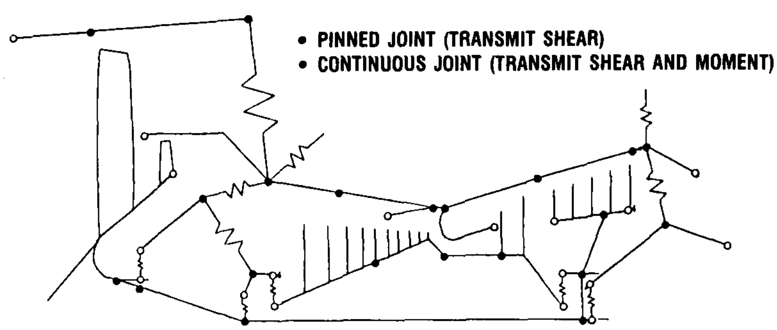
ROTOR SYSTEMS MODELING

Three nonlinear transient computer codes to model complex aerospace structures were developed. The first code, TRAN, integrates the physical system of equations and is used for short-time, high-frequency events. The next two programs, ARDS and TETRA, use component modal synthesis methods using an appropriate set of modes and are, therefore, more applicable for longer transients. The ARDS code has been enhanced to provide shock spectrum analysis and automatic optimum rotor design. The TETRA code can use either modal data generated by NASTRAN or experimental data and has been further enhanced by a steady-state analysis.

ROTOR SYSTEMS MODELING



ENERGY EFFICIENT ENGINE (E^3) SYSTEM (GENERAL ELECTRIC CONFIGURATION)



MODEL OF E^3 ENGINE SYSTEM

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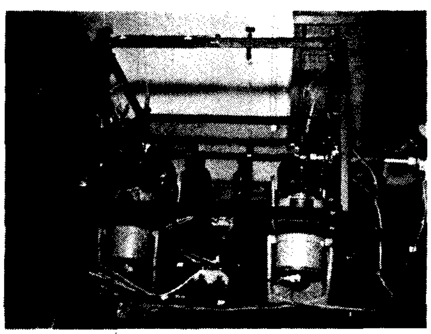
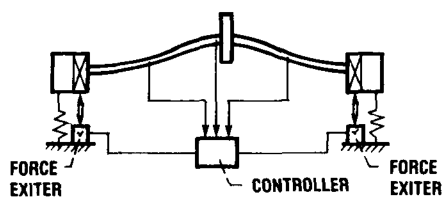
ACTIVE ROTOR CONTROL

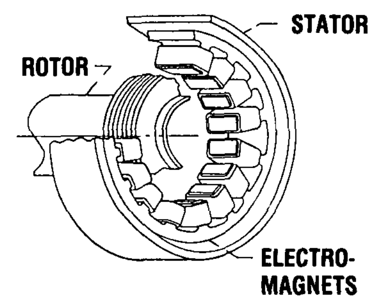
Active control of rotor vibrations offers important advantages over passive methods, especially greater damping. The principle is illustrated in the center of the figure. Shaft position sensors send signals to a controller which, guided by a control algorithm, operates actuators located at bearings. The actuators oppose undesired shaft vibrational motion. Three types of actuators are illustrated. In the upper left is a research rig with electromagnetic shakers. In the lower left is a group of three piezoelectric actuators, which change length when a voltage is applied to them. In the upper right is an electromagnetic device which both reduces vibration and replaces the conventional shaft bearings. Magnetic attraction between frame-mounted, fast-acting coils and iron disks mounted on and rotating with the shaft carries the weight of the shaft and exerts the vibration control forces. When sensors detect unwanted shaft movement, currents in the appropriate coils increase to pull the shaft back. This system permits higher shaft speed, automatic balancing, and better shaft positioning. Magnetic bearings need improvements in the speed and size of the electronics and in the actuator to meet flight requirements. Among the exciting possible advances in the actuator is the use of high-temperature superconductors which would make the windings more compact and eliminate the iron cores. The much more compact result is illustrated in the lower right.

ACTIVE ROTOR CONTROL

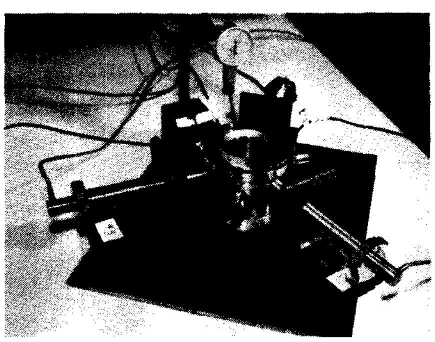


ACTIVE CONTROL TEST RIG

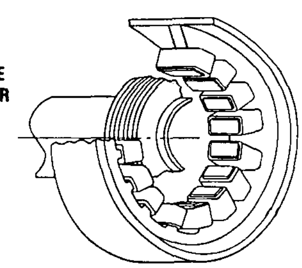




MAGNETIC BEARING



PIEZOELECTRIC ACTUATORS



MAGNETIC BEARING WITH HIGH-TEMPERATURE SUPERCONDUCTOR WINDINGS

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ROTOR DAMPERS

In conventional gas turbine engines, squeeze-film dampers are used to control nominal rotor unbalance. To control a transient blade-loss event, active damping may have to be used. The figure on the left shows a blade-loss test rig with piezoelectric actuators as active dampers. The object of the test was to investigate various algorithms to control the transient. A magnetic damper is being designed for this rig.

In the case of the space-plane, cryogenic fluids could be used as the fuel. At cryogenic temperatures there is no verified damper. There is a need for passive (or active) dampers. Potential passive cryo dampers are elastomeric, curved-beam, hydrostatic, closed-cartridge, non-Newtonian fluid, and eddy current. The figure on the right shows the liquid nitrogen damper test rig. A liquid hydrogen test rig is available.

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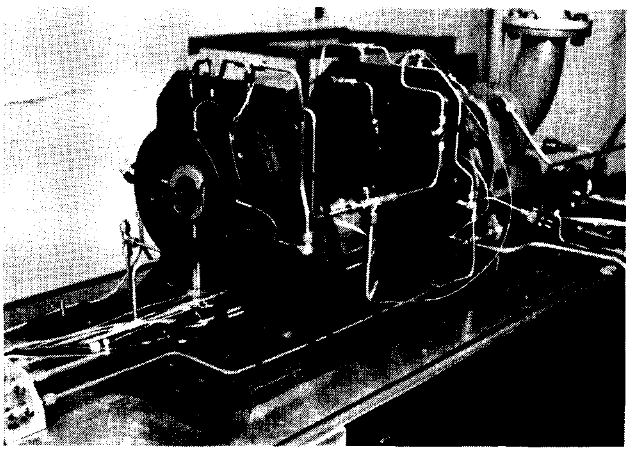
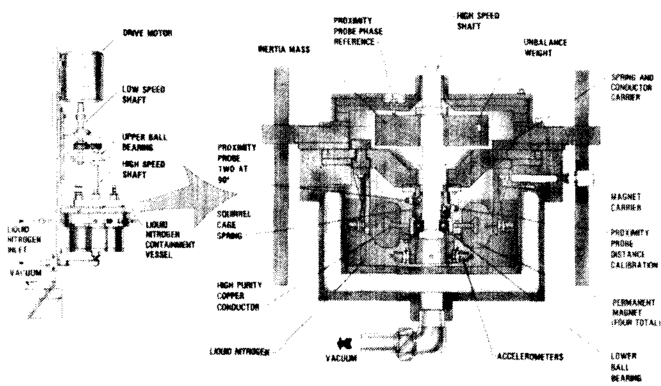
ROTOR DAMPERS



BLADE-LOSS TEST RIG



LIQUID NITROGEN DAMPER TEST RIG

CD-87-29589

HIGH-LOAD, THRUST-BEARING DAMPER RIG

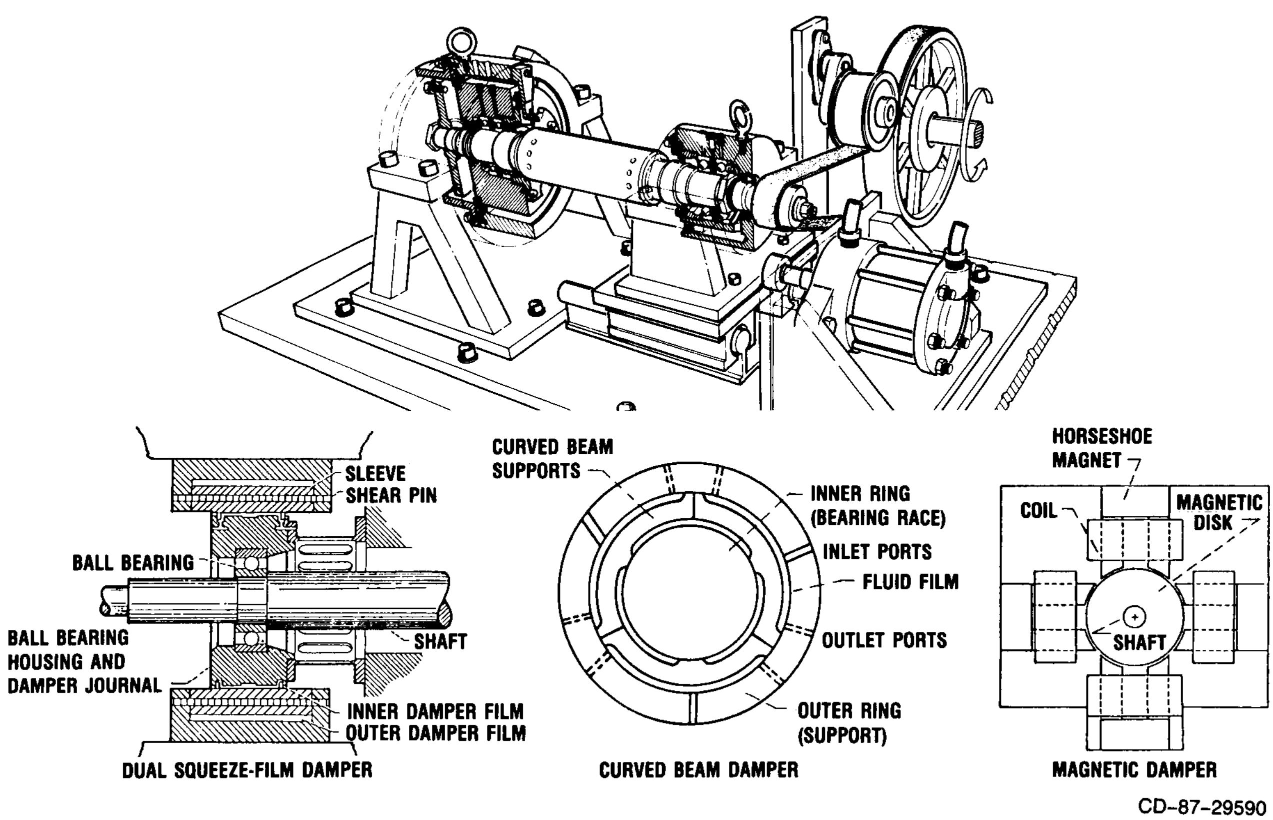
This rig was designed to test engine dampers which carry a larger than normal radial load (e.g., due to blade loss). It can also apply a thrust load to the test damper, for testing of radial dampers used at thrust bearing locations. The damper is loaded by unbalancing the disc at the left end of the shaft. Eddy current probes measure shaft and damper vibration, and quartz load washers measure the force applied to the damper. From these measurements, the stiffness and damping of the test damper can be calculated.

Three dampers are shown which may be tested in the rig. The dual squeeze-film damper has a conventional low-clearance film which provides the required damping at low imbalance levels. When the imbalance increases (as from a blade loss), a second, large-clearance film becomes active. This allows the damper amplitude needed to handle the higher imbalance.

The curve beam damper uses beam elements to provide stiffness. Fluid is forced through orifices to provide damping. This damper is inherently linear; stiffness and damping coefficients do not vary with vibration amplitude.

A magnetic damper applies a damping force to the rotor through electromagnets. The damper control system allows active control of rotor vibration, in which effective stiffness and damping are varied with speed and imbalance to optimize rotor performance.

HIGH-LOAD, THRUST-BEARING DAMPER RIG



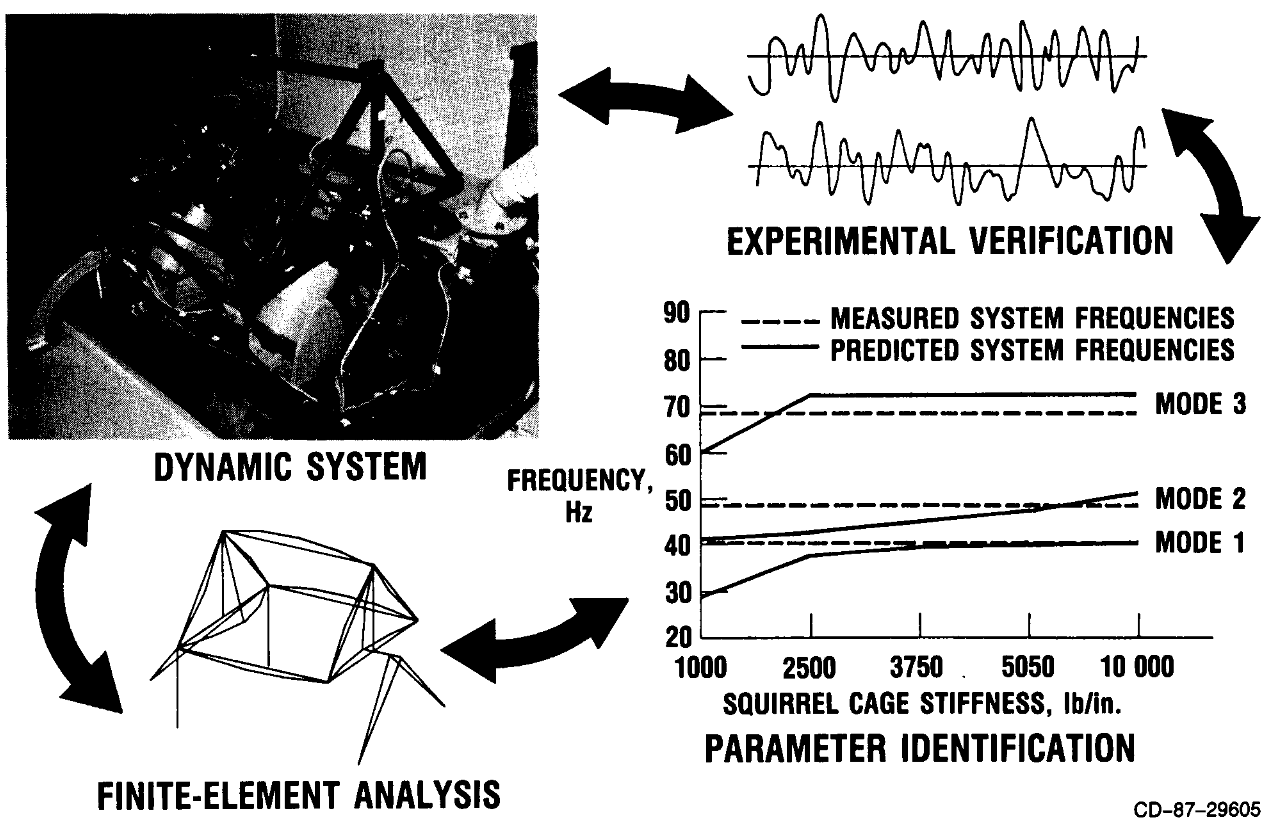
CHARACTERIZATION OF STRUCTURAL CONNECTIONS

An analytical and experimental program was carried out to develop improved methods for characterizing connections between structural components. Of particular interest was the identification of stiffness properties. The procedures developed in this program were evaluated with experimental vibration data obtained from the Rotating System Dynamics Rig.

Deficiencies in existing modeling techniques limit an analyst's ability to adequately model the connections between components. Connections between structural components are often mechanically complex, and hence very difficult to accurately model analytically. The influence that connections exert on overall system behavior can be profound. Thus, to refine the prediction of overall system behavior, improved analytical models for connections are needed.

Modeling accuracy is improved through the use of optimization methods by reducing discrepancies between the measured characteristics of an actual structural system and those predicted by an analytical model of the system. The approach used in this work involves modeling the system components with either finite elements or experimental modal data and then connecting the components at their interface points. Experimentally measured response data for the overall system are then used in conjunction with optimization methods to make improvements in the connections between components. The improvements in connections are computed in terms of physical stiffness parameters so that the physical characteristics of the connections can be better understood.

CHARACTERIZATION OF STRUCTURAL CONNECTIONS



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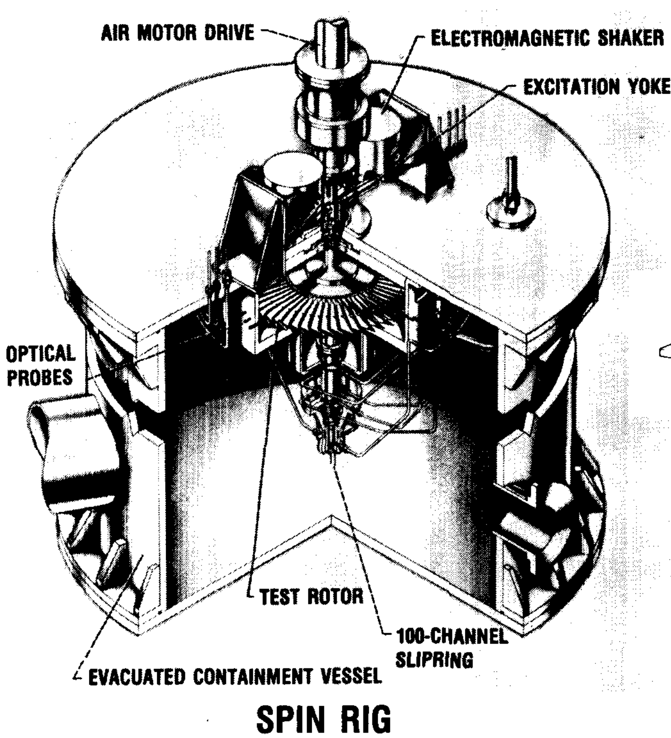
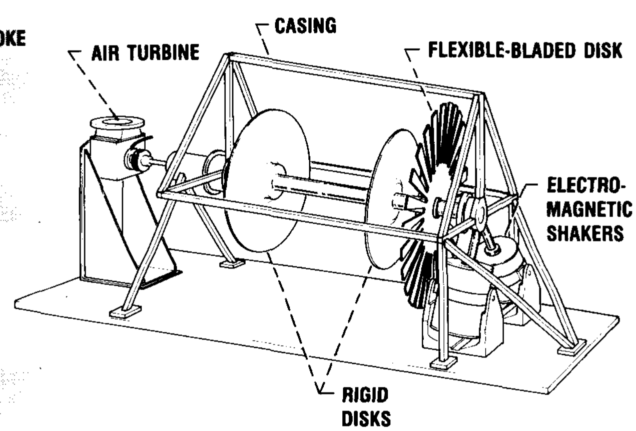
The Spin Rig is a facility which performs rotating dynamic spin tests of rotors in a vacuum to measure their vibratory and steady-state deflections and strains. The rotor wheel is contained in an armored test tank, where it can be spun up to 18 000 rpm. The tank can be evacuated to 0.001 atm, reducing air friction and blade loads to near zero. Up to 50 strain gages can be bonded to the rotor blades at strategic locations. These signals can be recorded on two 14-channel tape recorders. Data from the strain gages can then be analyzed. A laser system is also available to facilitate the measurement of centrifugally produced deflections.

The Rotating System Dynamics (RSD) Rig is a general facility for the purpose of determining the dynamic characteristics of rotating systems. Instrumentation consists of displacement measurement (9 channels); acceleration and velocity measurement (18 channels), and force measurement (4 channels). Fourteen channels of data can be recorded on tape, and all data can be monitored on oscilloscopes during testing. Four electrodynamic shakers, which are driven by a signal generator, provide forcing function input to the system under test. The rotating shafting is driven by an air turbine. Maximum rotating speed is currently 10 000 rpm.

PARAMETER VERIFICATION



SPIN RIG



ROTATING SYSTEMS DYNAMICS RIG

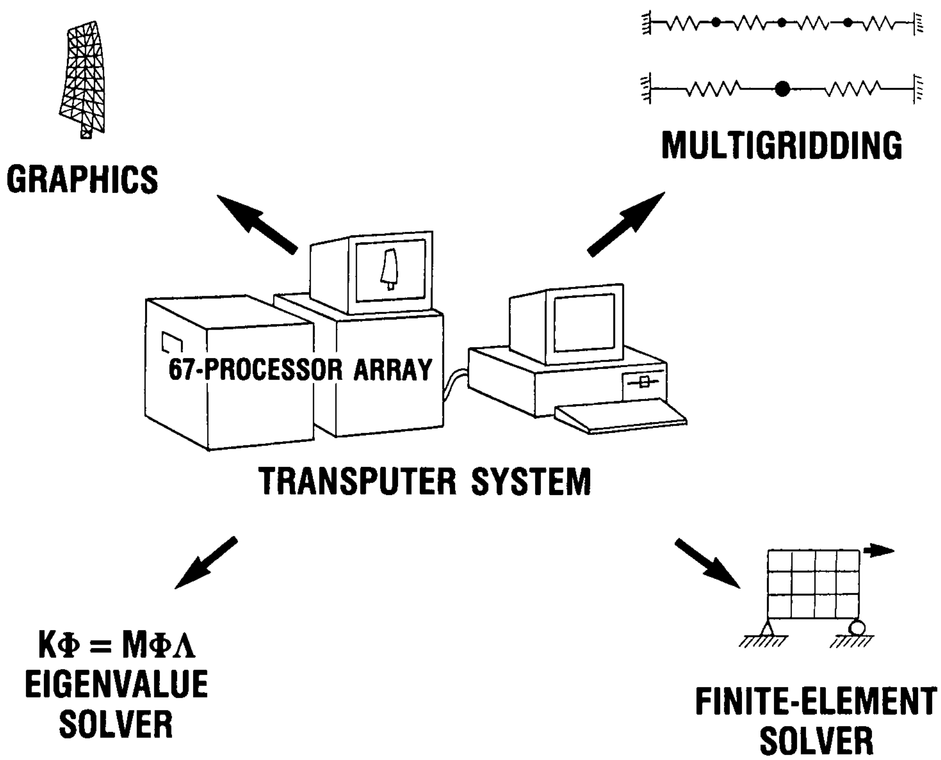
CD-87-29592

COMPUTATIONAL METHODS

Our computational methods research is directed to finding new and more efficient ways of performing structural computations. There is a heavy emphasis on emerging parallel processing methods. Our research uses many different mainframe computers as well as our transputer system. A 67-processor transputer system is used for most of our parallel methods research. This system is designed to be electronically reconfigured into a variety of different equivalent architectures so that the interplay between algorithms and architectures can be fully explored. The system is built with high-performance processors, but is not expected to perform as well as a dedicated function computer could. When new methods are fully developed, they will be transferred to larger dedicated computer facilities within the NASA computer network.

In one approach, finite-element analyses are conducted by distributing stiffness matrices throughout the processor array. Multigridding analysis methods, which employ successive refinement of mesh sizes, have the refined meshes assigned to successive processors. Problems involving the management of global variables are being studied in order to distribute graphics primitives to a processor array to support high-speed animation. Eigenvalue solution routines which employ recursive, binary, tree-structured search algorithms are taking advantage of the transputer network ability to reconfigure processor interconnections.

COMPUTATIONAL METHODS



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LIFE PREDICTION TECHNOLOGIES FOR AERONAUTICAL PROPULSION SYSTEMS

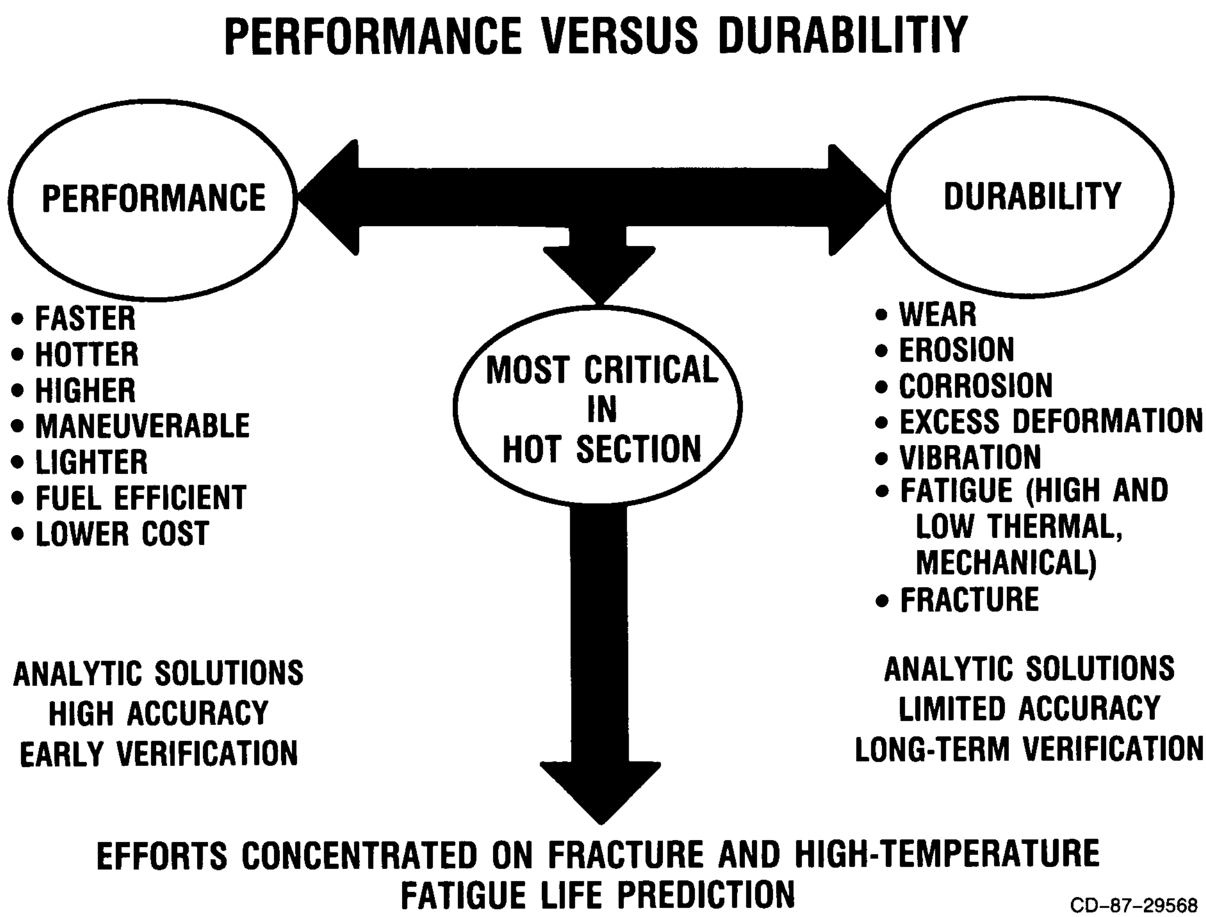
Michael A. McGaw

ABSTRACT

Fatigue and fracture problems continue to occur in aeronautical gas turbine engines. Components whose useful life is limited by these failure modes include turbine hot-section blades, vanes, and disks. Safety considerations dictate that catastrophic failures be avoided, while economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The decision in design is therefore making the tradeoff between engine performance and durability. The NASA Lewis Research Center has contributed to the aeropropulsion industry in the area of life prediction technology for over 30 years, developing creep and fatigue life prediction methodologies for hot-section materials. At the present time, emphasis is being placed on the development of methods capable of handling both thermal and mechanical fatigue under severe environments. Recent accomplishments include the development of more accurate creep-fatigue life prediction methods such as the total strain version of Lewis' Strainrange Partitioning (SRP) and the HOST-developed Cyclic Damage Accumulation (CDA) model. Other examples include the development of a more accurate cumulative fatigue damage rule - the Double Damage Curve Approach (DDCA), which provides greatly improved accuracy in comparison with usual cumulative fatigue design rules. Other accomplishments in the area of high-temperature fatigue crack growth may also be mentioned. Finally, we are looking to the future and are beginning to do research on the advanced methods which will be required for development of advanced materials and propulsion systems over the next 10 to 20 years.

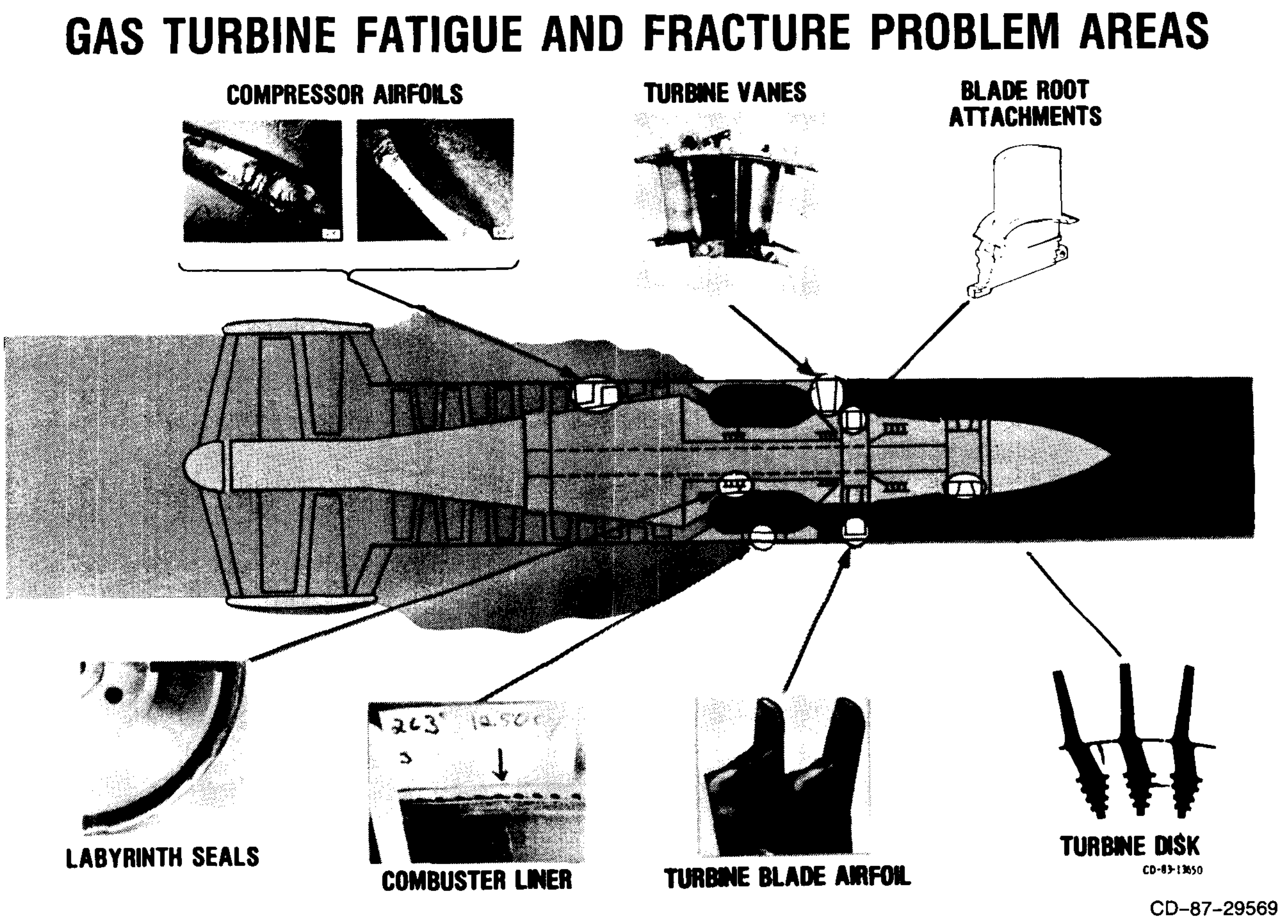
PERFORMANCE VERSUS DURABILITY

Fatigue and fracture problems continue to occur throughout aeronautical gas turbine engines. Safety considerations dictate that life-threatening catastrophic failures be avoided, and economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The failure rate, however, can be related directly to the performance extracted from the machine. We thus have the perennial dichotomy: performance versus durability. Because the primary driver for aeropropulsion is performance, we must view lack of adequate durability as a constraint to the desired performance. Knowledge of both aspects is necessary to understand and quantify the tradeoffs between the two. Performance may take a variety of forms, some of which are listed in the figure. Similarly, various failure modes are noted which give rise to the overall durability. Nowhere is the tradeoff more critical than in the hot section, where all of the failure modes are present in varying degrees.



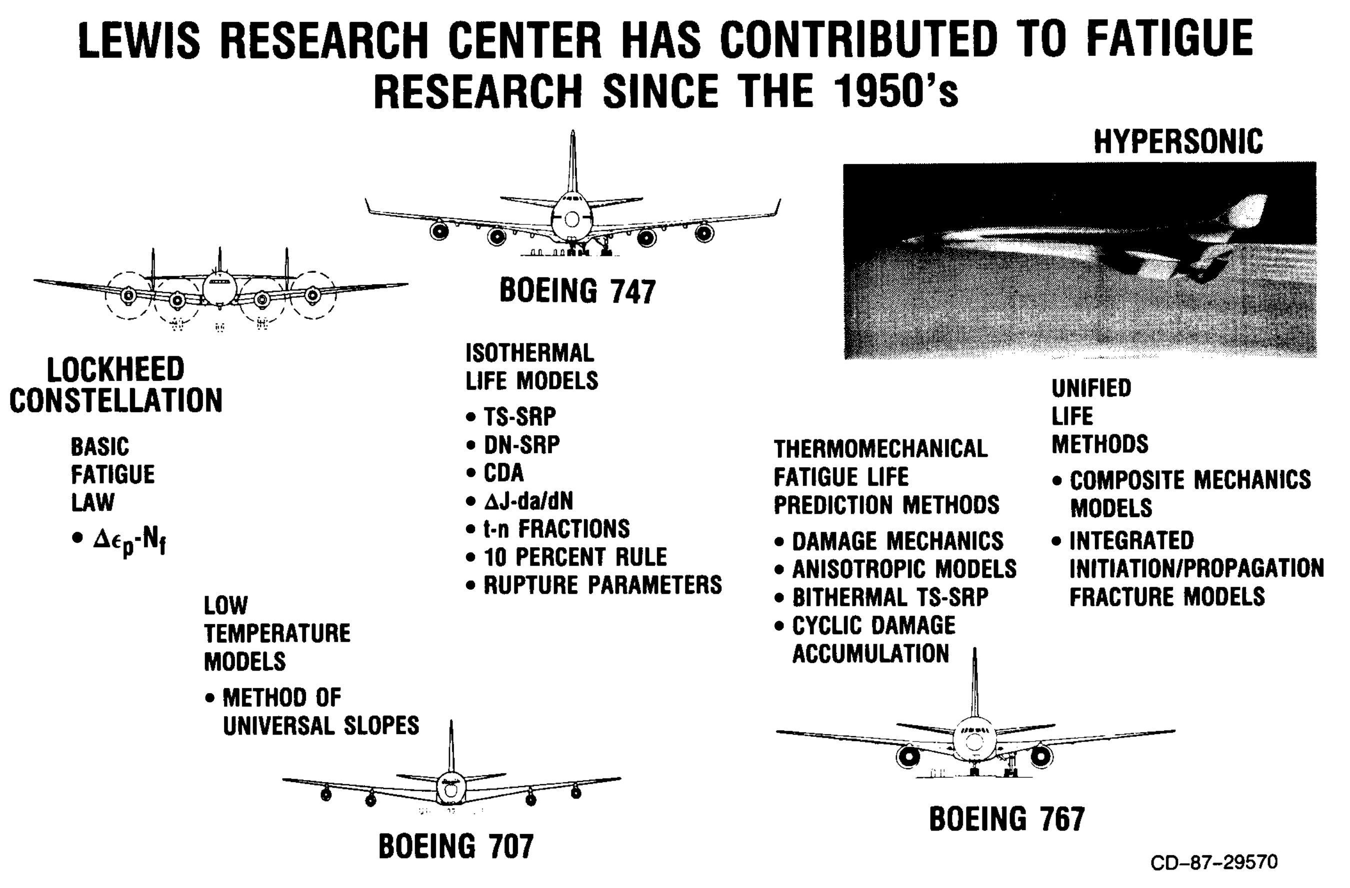
GAS TURBINE FATIGUE AND FRACTURE PROBLEM AREAS

This figure illustrates typical components that have exhibited histories of limited durability. Compressor blades, combustor liners, guide vanes, turbine blades, disks, shafts, bearings, and spacers are just a few of the more common components that have exhibited cyclic crack initiation, propagation, and fracture phenomena. These failure phenomena arise because of repeated thermal and/or mechanical loading induced by the service cycle.



LEWIS RESEARCH CENTER CONTRIBUTIONS

At the Lewis Research Center, we have aided the aeropropulsion industry by concentrating on developing fracture and elevated-temperature fatigue life prediction methods. As aeropropulsion became more sophisticated and advanced materials were developed, we increased our level of intensity and degree of sophistication in life prediction modeling. At the present time, emphasis is placed on methods capable of dealing with both thermal and mechanical fatigue under severe environments. The methods listed in the heavy-lined box are the ones we are currently pursuing, and as such, they are too new to have been used in hardware. We are also looking to the needs of the future and are beginning to do research on the advanced methods that will be required of advanced materials and propulsion systems over the next 10 to 20 years.



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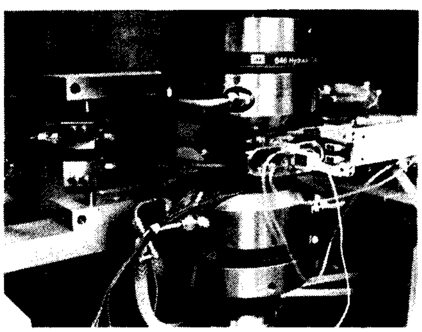
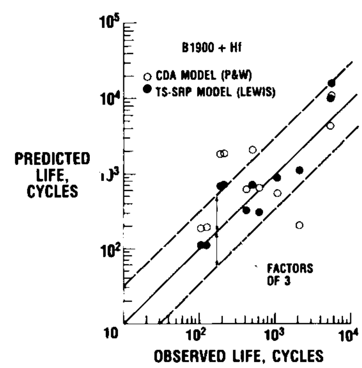
HIGH-TEMPERATURE FATIGUE CRACK INITIATION

In this figure, we compare the predictive accuracy of two relatively recent (1983, 1984) isothermal life prediction methods for fatigue crack initiation (0.030-in.-length surface crack): the HOST Cyclic Damage Accumulation (CDA) model developed by Pratt & Whitney under contract to Lewis, and the total strain version of Lewis' Strainrange Partitioning (TS-SRP). Note the rather sizeable factors of ±3 in our inability to predict the high-temperature, low-cycle fatigue lives of coupons of a cast nickel-base turbine alloy. Factors of safety of nearly an order of magnitude on average life would have to be applied if these methods were to be used in a design situation. While this appears to be a very large factor, it is considerably less than would be required by alternate methods.

HIGH-TEMPERATURE FATIGUE CRACK INITIATION

ISOTHERMAL VERIFICATION





CYCLIC DAMAGE ACCUMULATION (CDA) MODEL INSET

$$\dot{\epsilon}_{Pnet} - \int_0^N \left[\frac{dD}{dN}\right]_{Ref} \times \left\{ \left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\left(\frac{\Delta\sigma}{\Delta\sigma_{Ref}}\right) + \left[\left(\frac{\Delta\sigma_{Ref}}{\Delta\sigma}\right)\left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\right]^{B'} \times \left[\left(\frac{t}{t_{Ref}}\right)^{C'} - 1\right] \right\} dN = 0$$

TOTAL STRAIN, STRAINRANGE PARTITIONING (TS-SRP)

$$\Delta\epsilon = C' \left[K_{ij}\, N_f^{\,b} + N_f^{\,c} \right]$$

$$C' = \left[\Sigma\, F_{ij} (C_{ij})^{1/c} \right]^{c}$$

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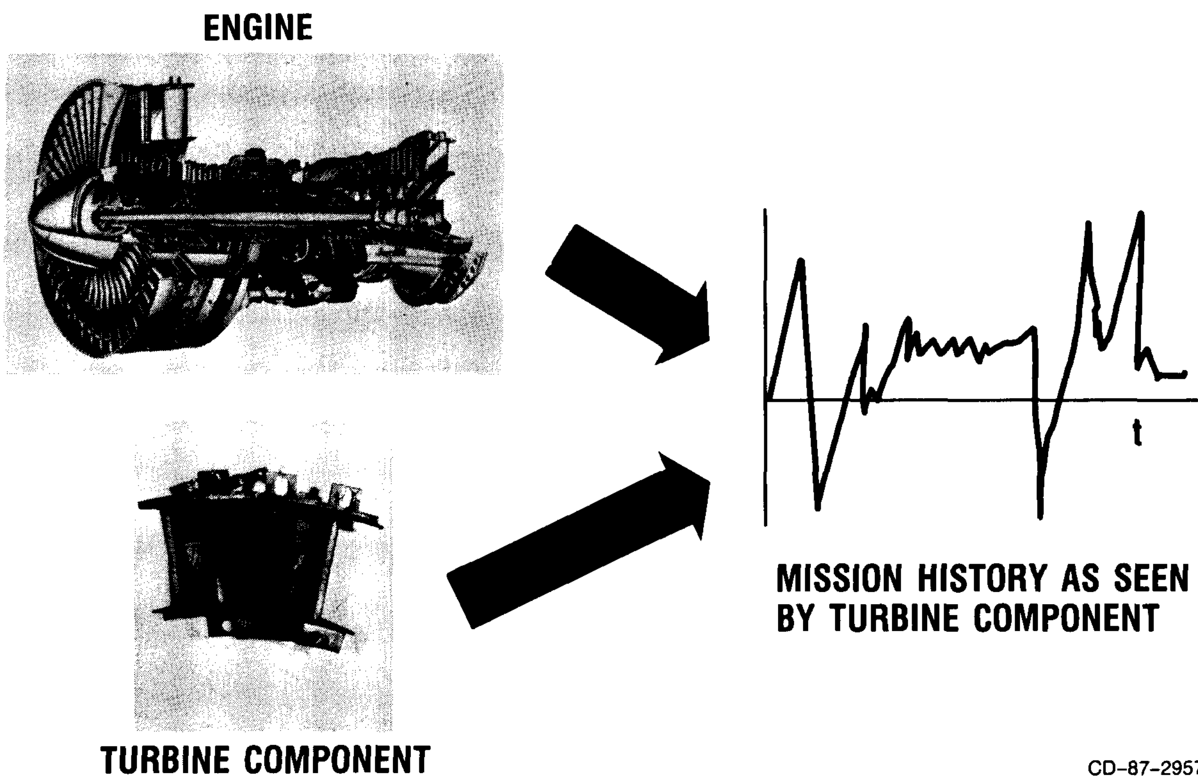
COMPLEX COMPONENT LOADING HISTORIES

Mission profiles resolve into complex thermal and mechanical loading histories on many components. Components whose lives are limited as a result undergo creep and fatigue in varying and interacting degrees, which eventually lead to failure. One such typical component is a hot-section turbine blade. In this figure we see the mechanical load history induced by the mission cycle as seen from the life-limiting, or critical, location of the turbine blade.

MISSION HISTORY PRODUCES COMPLEX COMPONENT LOADING HISTORIES



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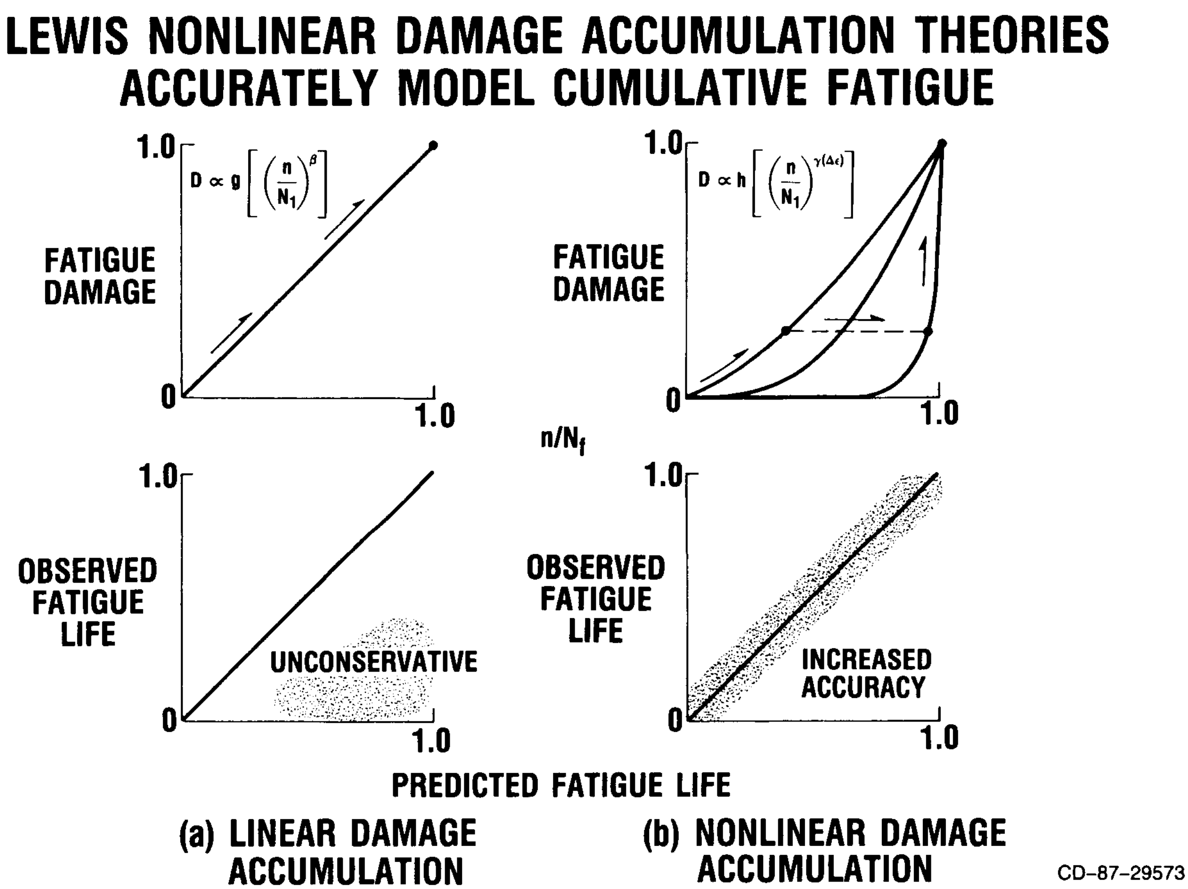
A MORE ACCURATE CUMULATIVE FATIGUE DAMAGE RULE

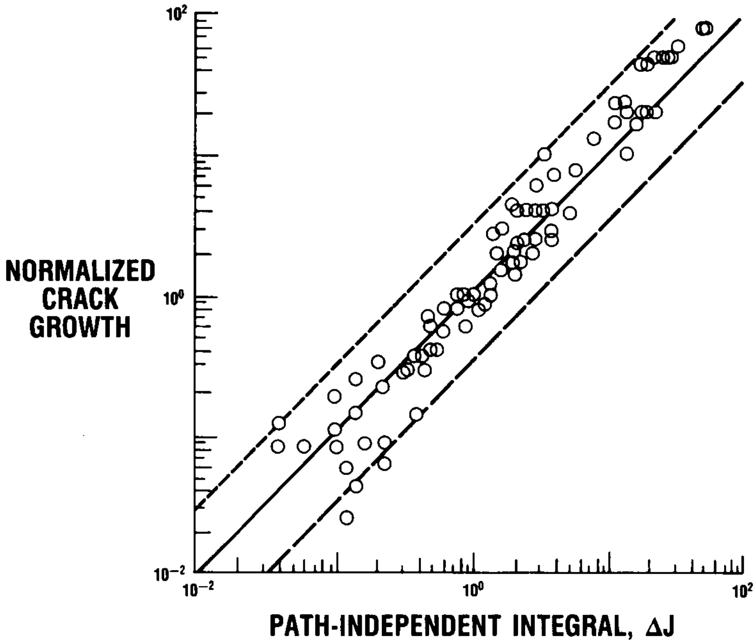
When considering the life of components subjected to complex mechanical loading histories, it is common to use a fatigue crack initiation life criterion in conjunction with a suitable damage accumulation expression. Traditionally, the damage accumulation expression used is the classical Linear Damage Rule. While this rule simplifies life prediction calculations, it can often result in unconservative designs, especially under certain loading conditions. An advancement in increasing the accuracy of life predictions by using a nonlinear damage accumulation rule was made at Lewis recently. This new expression, called the Double Damage Curve Approach, accounts for loading level dependence in damage evolution. The resulting increase in predictive accuracy is substantial, as much as nearly an order of magnitude improvement over the Linear Damage Rule.



High and low-temperature cyclic crack propagation life predictions based upon the concepts of path-independent integrals and crack tip oxidation mechanisms are shown for turbine alloys. This life prediction method is the result of several years of research conducted by H.W. Liu of Syracuse University under the HOST sponsorship of NASA Lewis. Note again the rather sizeable scatter of factors of three on crack propagation rate even for well-controlled laboratory coupon tests.

ISOTHERMAL FATIGUE CRACK PROPAGATION MODEL

ΔJ PARAMETER FOR LOW TEMPERATURE
OXIDATION MODEL FOR HIGH TEMPERATURE



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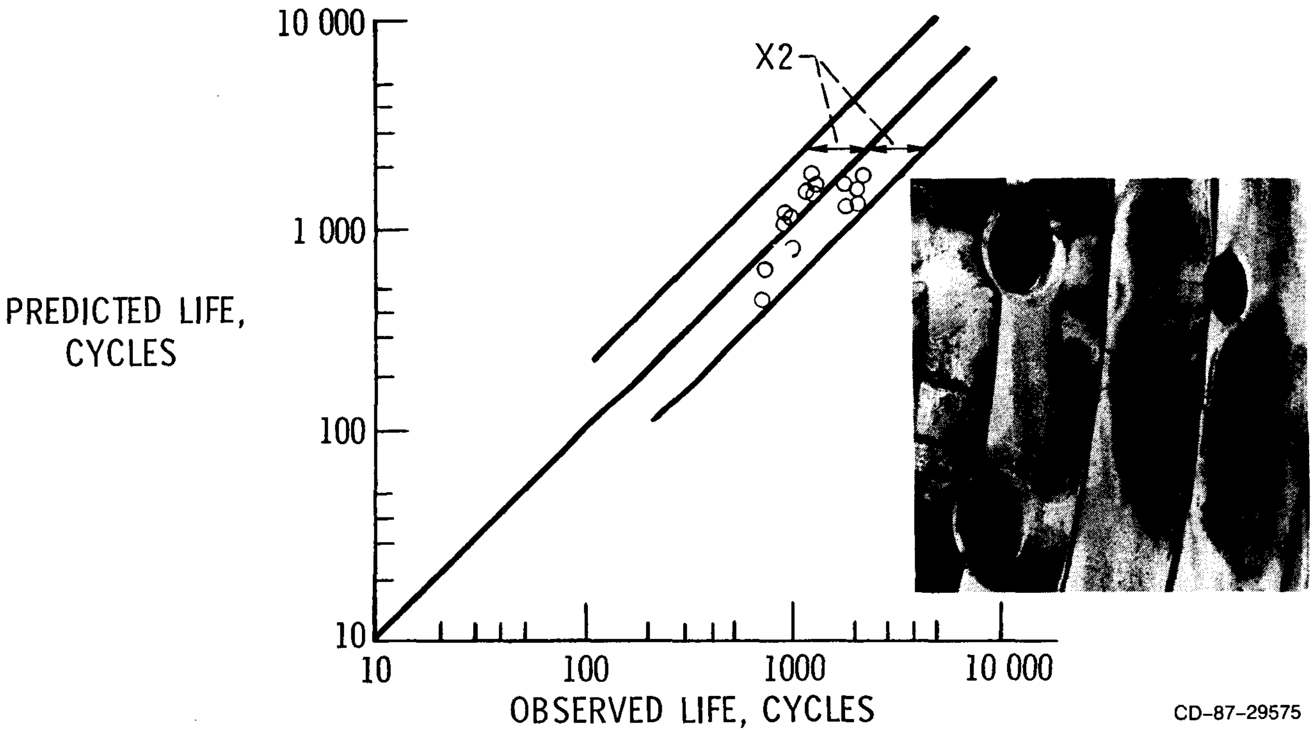
COMBUSTOR LINER STRUCTURAL AND LIFE ANALYSIS

An application of the Lewis-originated creep-fatigue life prediction method, Strainrange Partitioning (for crack initiation), is shown in this figure. Pratt & Whitney modified the approach to suit their unique requirements and used the method in the design and evaluation of combustor liners in the JT9D high-bypass-ratio engine. Factors of about ±2 in cyclic lifetime are noted by the upper and lower bound lines. This remarkable good accuracy is obtained, in part, by the manner in which the Pratt & Whitney version of the method is calibrated to the failure behavior of real hardware. The variation in predicted lives results from different engine usage which can be accommodated by the predictive method.

ACCURACY OF PRATT & WHITNEY'S VERSION OF DUCTILITY NORMALIZED STRAINRANGE PARTITIONING IN PREDICTING COMBUSTOR LINER LIFE IN HIGH-BYPASS-RATIO ENGINES



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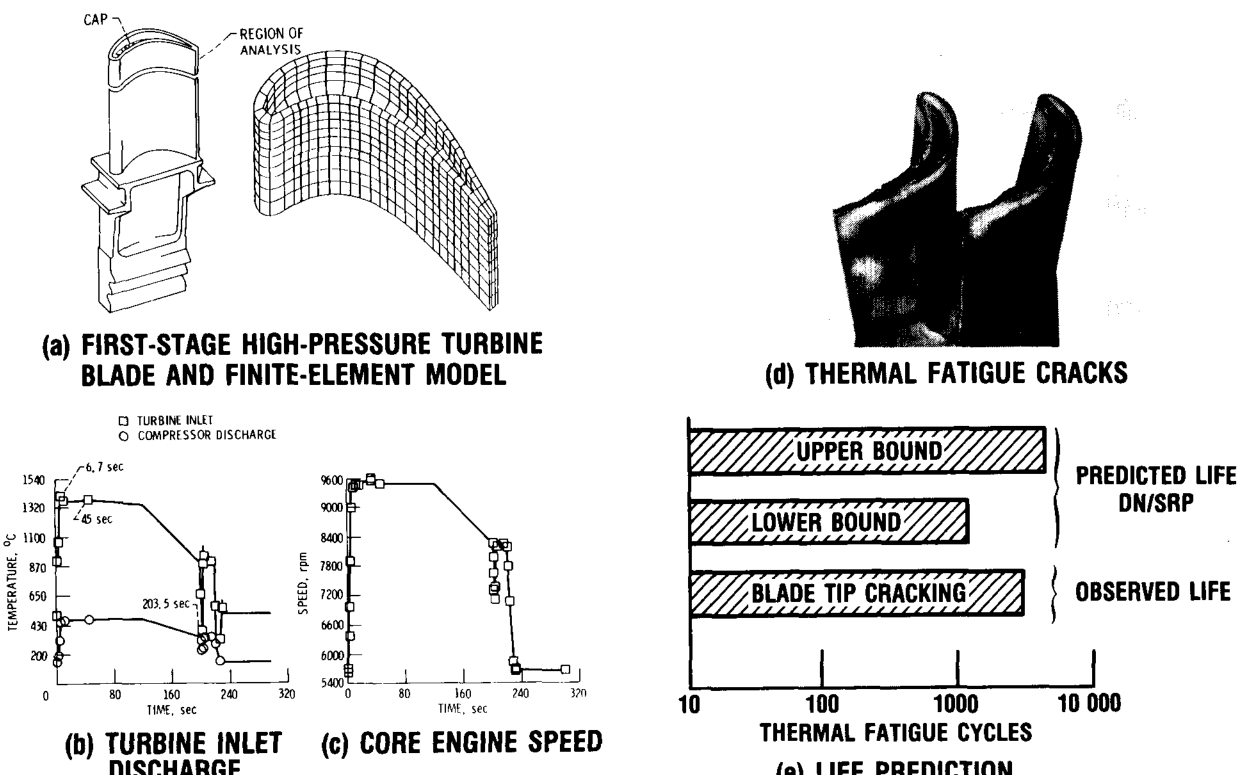
TURBINE BLADE STRUCTURAL AND LIFE ANALYSIS

In another application of the Lewis-originated creep-fatigue life prediction method, Strainrange Partitioning, the General Electric Company analyzed an air-cooled turbine blade, making an assessment of expected service life. This particular blade, a first-stage, high-pressure turbine blade, is subjected to cyclic thermal straining in the tip cap region because of the service history involved. After conducting a thermal analysis and a nonlinear structural analysis of the cap region, an assessment of component life was performed. The analysis was supplemented by laboratory experiments on the blade alloy for the temperature-strain history calculated from the analysis. Strainrange Partitioning was found to predict component life over a range which spanned the observed service life.

TURBINE BLADE STRUCTURAL AND LIFE ANALYSIS



(a) FIRST-STAGE HIGH-PRESSURE TURBINE BLADE AND FINITE-ELEMENT MODEL

(d) THERMAL FATIGUE CRACKS

(b) TURBINE INLET DISCHARGE TEMPERATURES

(c) CORE ENGINE SPEED

(e) LIFE PREDICTION

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BRITTLE MATERIALS DESIGN METHOD

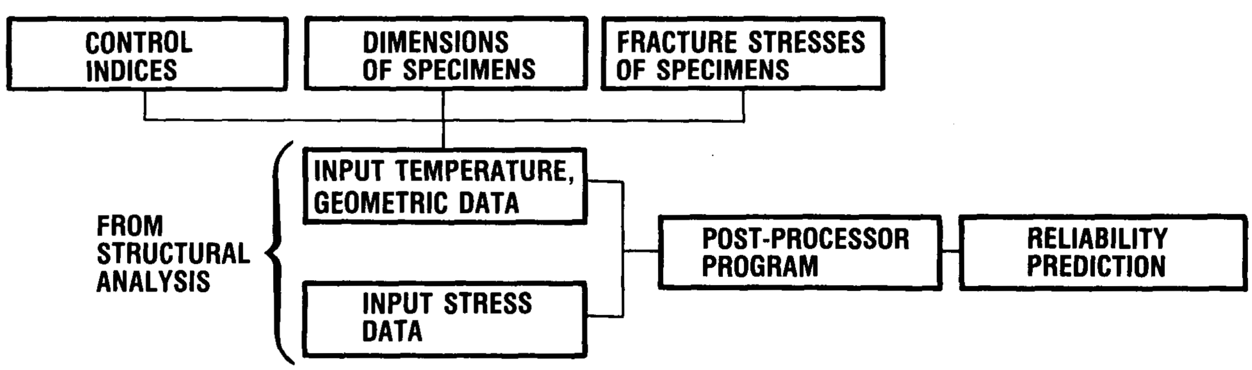
The design of brittle ceramics differs from that of ductile metals because of the inability of ceramic materials to redistribute high local stresses caused by inherent flaws. Random flaw size and orientation require that a probabilistic analysis employing the weakest link theory be performed if the component reliability is to be determined. The lack of adequate design technology, such as general purpose design programs, standards, nondestructive evaluation (NDE) expertise, and codes of procedure has prompted NASA Lewis to initiate research focused on ceramics for heat engines at the beginning of this decade. One of the early accomplishments of this effort has been the development of the unique, public-domain design program called Structural Ceramics Analysis and Reliability Evaluation (SCARE). It is still under development, with new enhancements in improved fast fracture and time-dependent reliability analysis being added and validated.

CERAMICS/BRITTLE MATERIALS LIFE PREDICTION TECHNOLOGY

MATERIAL BRITTLENESS AND PRESENCE OF DEFECTS REQUIRE

- **PROBABILISTIC APPROACH ALLOWING FOR STRENGTH DISPERSION**
- **USE OF WEAKEST LINK THEORY TO TREAT SIZE EFFECT**
- **REFINED THERMAL AND STRESS ANALYSIS—FIELD SOLUTIONS**

RELIABILITY ANALYSIS CODE (SCARE)



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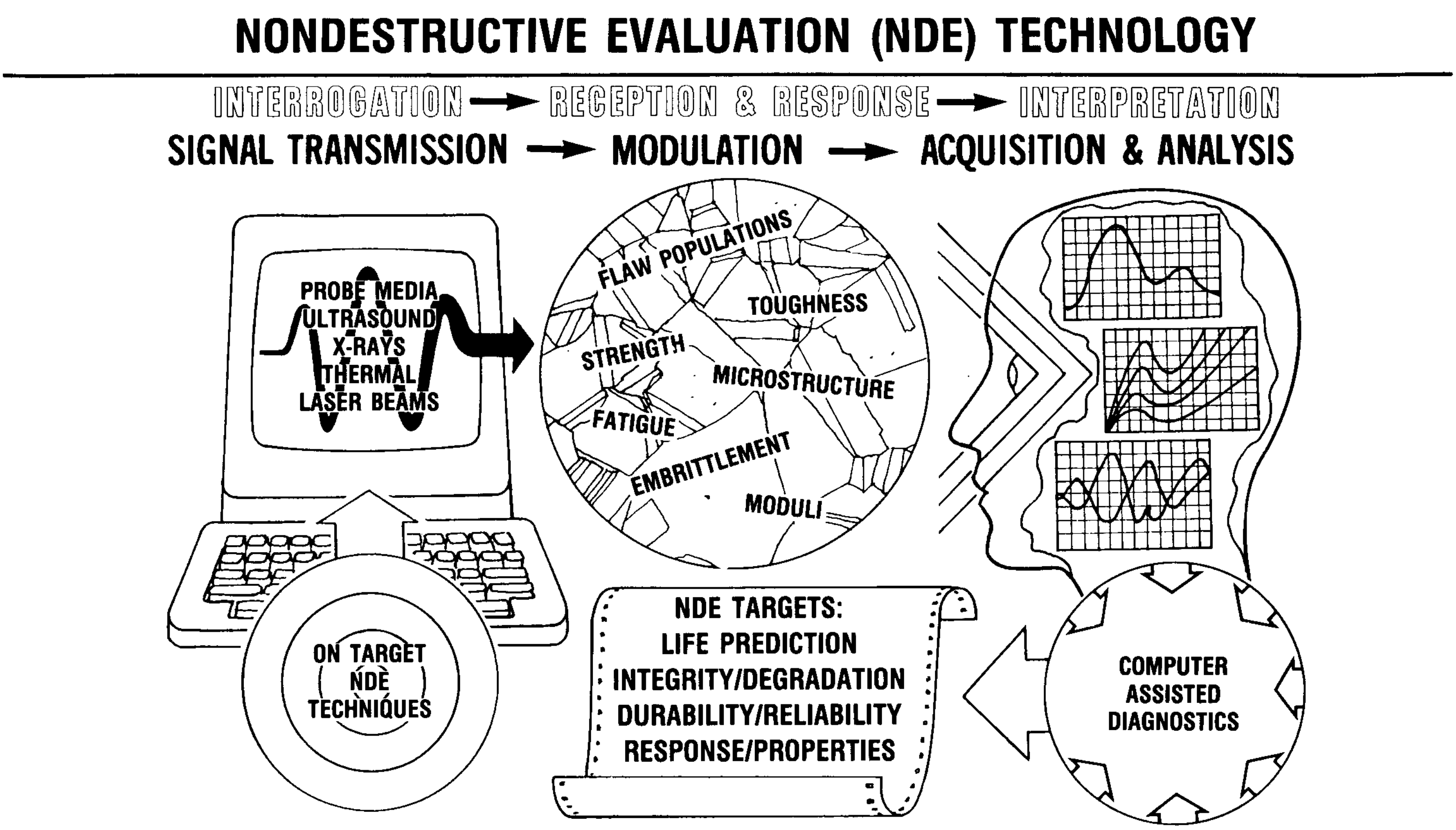
NONDESTRUCTIVE EVALUATION (NDE) TECHNOLOGY

The need for nondestructive materials characterization is indicated where local properties are critical or where the presence, identity, and distribution of potentially critical flaws can only be assessed statistically. In the latter case, flaws can be so microscopic, numerous, and dispersed that it is impractical to resolve them individually. Large populations of nonresolvable flaws may interact with each other (e.g., surface versus volume flaws) or with morphological anomalies. These interactions would be manifested as degraded bulk properties (e.g., deficiencies in strength and toughness). Although a structure may be free of discrete critical flaws, it may still be susceptible to failure because of inadequate or degraded intrinsic mechanical properties. This can arise from faulty material processing and/or degradation under aggressive service environments. It is important, therefore, to have nondestructive methods for quantitatively characterizing mechanical properties.



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INTEGRATED ANALYSIS AND APPLICATIONS

Dale A. Hopkins

ABSTRACT

A select overview is provided of ongoing research efforts which, in the broadest sense, are all focused toward the development and verification of integrated structural analysis and optimal design capabilities for advanced aerospace propulsion and power systems. The overview incorporates a variety of subject areas including:

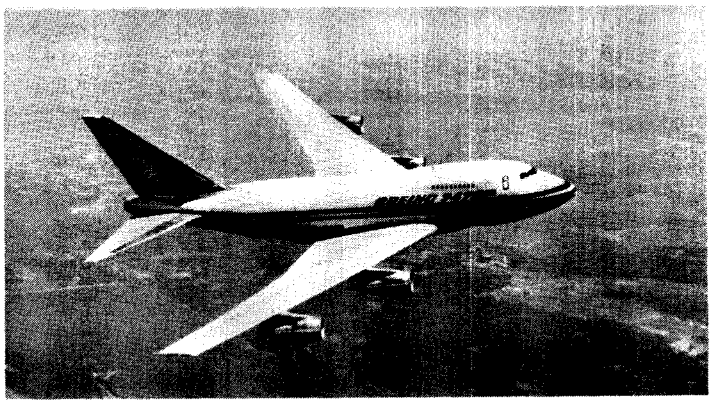
(1) Composites - analytical models (composite mechanics), integrated computational methods, and experimental characterization of composite structural response and durabilty for resin-, metal-, and ceramic-matrix systems
(2) Advanced inelastic analysis - algorithms/numerical methods for more accurate and efficient analysis
(3) Constitutive modelling - theoretical formulation and experimental characterization of thermoviscoplastic material behavior
(4) Computational simulation - engine structures from components to assemblies and up to an entire engine system subjected to simulated test-stand and mission load histories
(5) Probabilistic structural analysis - quantification of the effects of uncertainty in geometry, material, loads, and boundary conditions on structural response for true reliability assessment
(6) Interdisciplinary optimization - incorporation of mathematical optimization and multidisciplinary analyses to provide streamlined, autonomous optimal design systems

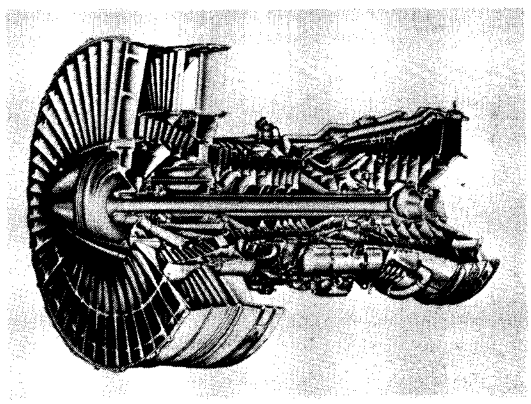
Specific examples are presented which illustrate the utility of these advnced technologies for real-world applications.

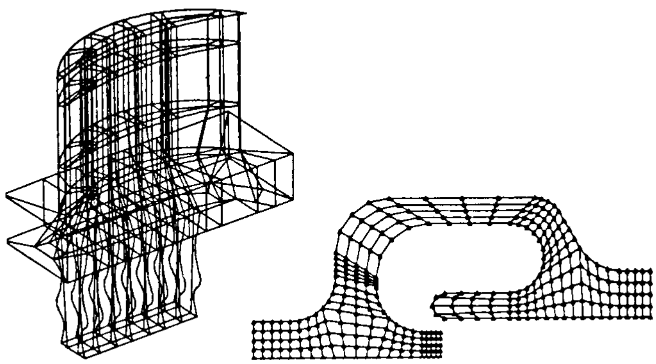
3-D INELASTIC STRUCTURAL ANALYSIS METHODS

The desire for increased performance/efficiency of gas turbine engines has led to designs having more severe operating cycles - i.e., higher pressures and temperatures. The general result has been an exhibited decrease in engine durability with an associated increase in maintenance costs, particularly in the hot section where more hostile environments accelerate component wear and damage. Reliable, cost-effective design to achieve prescribed component durability requires effective (i.e., accurate and efficient) structural analysis tools that account for the complex geometries, loading conditions, and forms of nonlinear material respons that characterize these components in their operating environment.

3-D INELASTIC STRUCTURAL ANALYSIS METHODS







- MATERIAL NONLINEARITIES
- GEOMETRIC NONLINEARITIES
- TEMPERATURE DEPENDENCE
- TIME DEPENDENCE

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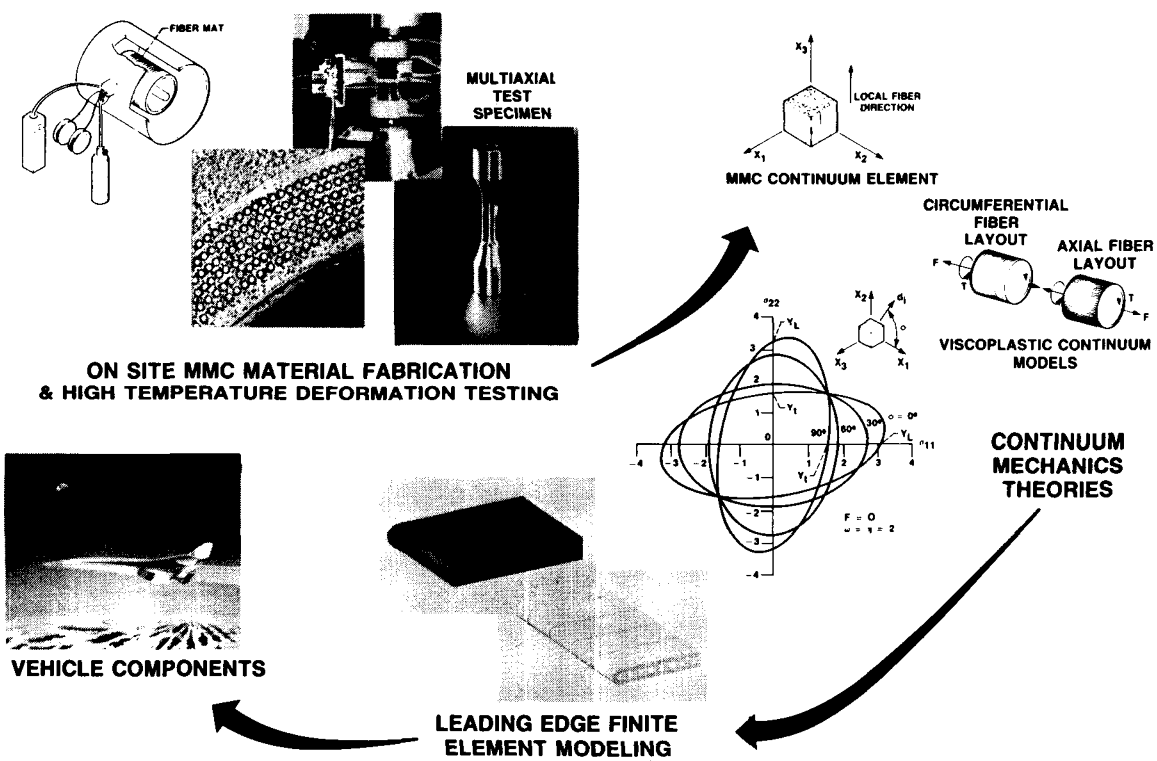
LEWIS' UNIQUE ROLE IN METAL-MATRIX COMPOSITE TECHNOLOGY

Through a cooperative effort between the Structures and Materials Divisions, Lewis Research Center can boast of having a unique capability in metal-matrix composite (MMC) technology. The Materials Division is capable of fabricating thin-walled tubular MMC specimens which are then tested by the Structures Division under axial-torsional conditions at elevated temperatures. From these tests the necessary material functions and parameters can be determined for viscoplastic constitutive models that are also developed at Lewis. The constitutive models, in turn, are implemented into advanced structural analysis computer codes to predict the response of MMC components subjected to complex thermomechanical loading histories. These analyses provide important information to aid the engineer in making design decisions for actual aerospace vehicles.

LEWIS' UNIQUE ROLE IN METAL-MATRIX COMPOSITE (MMC) TECHNOLOGY



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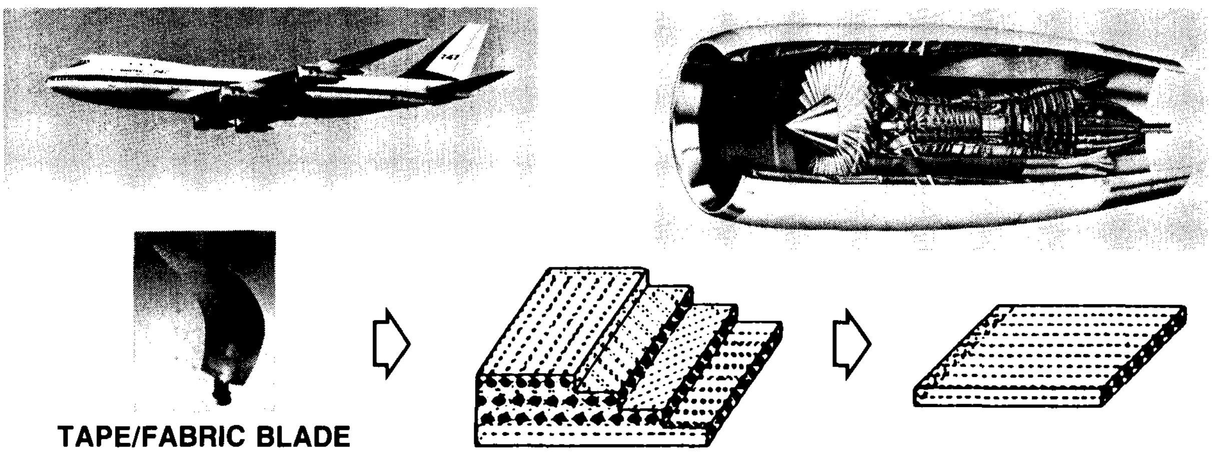
INTEGRATED COMPOSITES ANALYZER

The numerous properties needed for composite structural design, combined with the difficulty of obtaining experimental measurements of these properties, have motivated development of the Integrated Composites Analyzer computer code. The code incorporates the appropriate composite mechanics to analyze/design multilayered fiber composites for arbitrary hygrothermal environments. Input variables to the code include material systems, volume fractions, laminate configurations, fabrication conditions, and service environment. The Integrated Composites Analyzer predicts virtually all composite hygral, thermal, and mechanical properties necessary to perform structural/stress analysis, and it has proven to be an effective tool for preliminary design of composite structures. Confidence in the predictive capabilities of the code has been established through excellent agreement with experimental data obtained for a variety of composite systems in extreme hygrothermal environments.

INTEGRATED COMPOSITES ANALYZER (ICAN)



ICAN COMPARISON

LONGITUDINAL ELASTIC MODULUS, ksi

LAMINATE MATERIAL	EXPERIMENTAL −300 °F	EXPERIMENTAL 70 °F	EXPERIMENTAL 200 °F	ICAN PREDICTIONS −300 °F	ICAN PREDICTIONS 70 °F	ICAN PREDICTIONS 200 °F
7781E-GLASS CLOTH	4600	4370	3970	4589	4251	4076
7576E-GLASS CLOTH	6540	6020	6050	5587	5395	5457
REPRESENTATIVE	5320	4370	4150	4440	4114	3948

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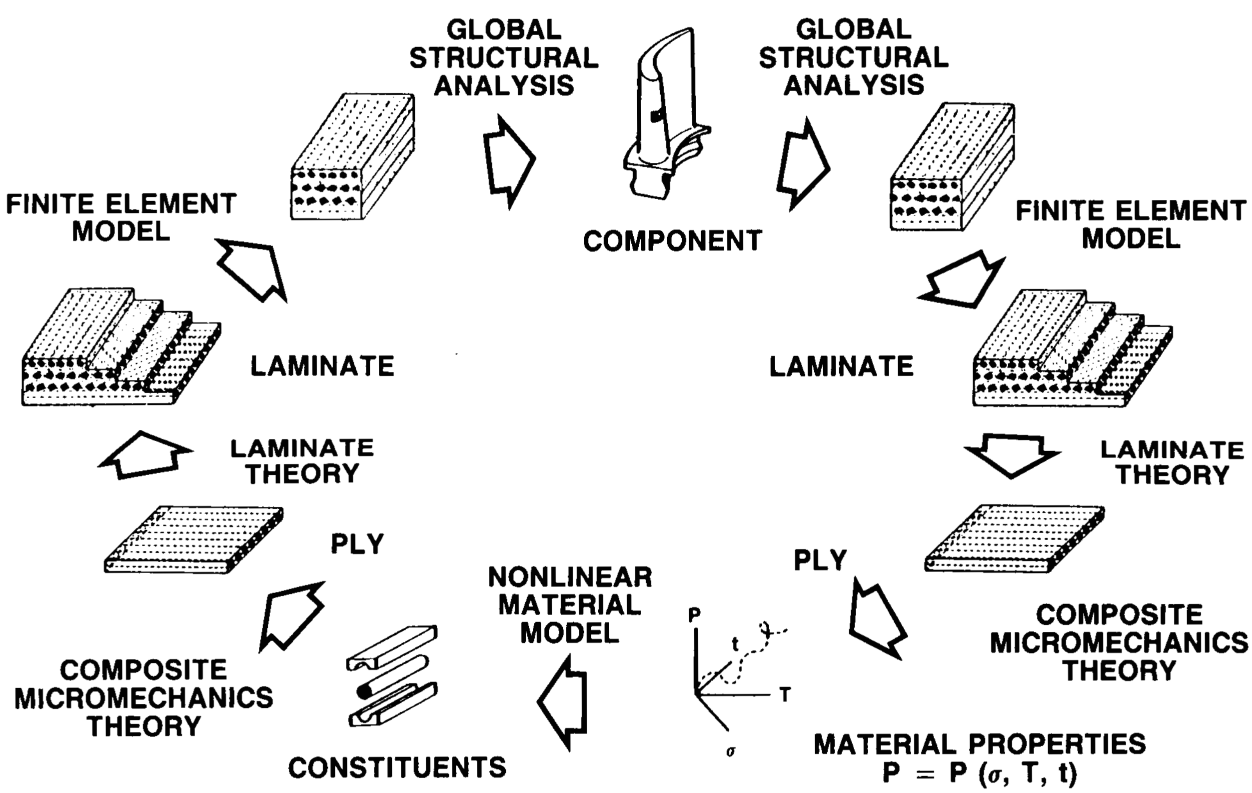
STRUCTURAL ANALYSIS FOR HIGH-TEMPERATURE COMPOSITES

The mechanical performance and structural integrity of composites are ultimately governed by the behavior of the local constituents (i.e., fiber, matrix, and interphase). This local constituent behavior is dynamic, particularly in high-temperature applications, and complex due to various nonlinearities associated with, for example, large stress/strain excursions, temperature-dependent material properties, and time-dependent effects. In the analysis/design of a composite structure, it is essential to be able to track this local behavior and relate its effects on global structural response. The integrated approach illustrated provides this capability by incorporating constituent material models/cumulative damage models, composite mechanics (micro and macro), and global structural analysis.

STRUCTURAL ANALYSIS FOR HIGH-TEMPERATURE COMPOSITES



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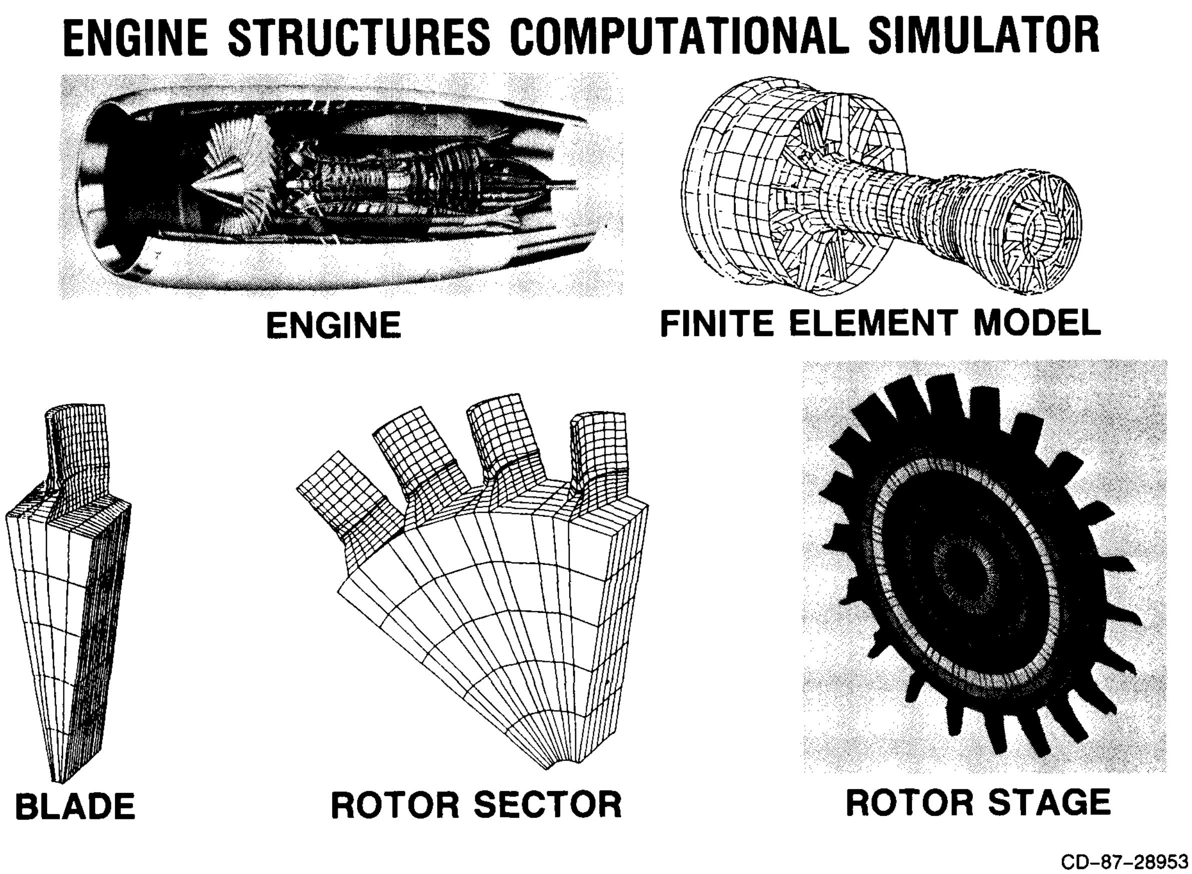
ENGINE STRUCTURES COMPUTATIONAL SIMULATOR

The Engine Structures Computational Simulator is intended to simulate the structural behavior/performance at test-stand and/or flight-mission conditions. The simulation can be for subcomponents, components (turbine blade), subassemblies (rotor sector), assemblies (rotor stage), and up to the entire engine. New design concepts, materials, mission requirements, etc., can be simulated and their potential benefits evaluated prior to detail design and testing initiation. Local or subcomponent damage effects on engine structural performance can be assessed and engine structural durability/integrity determined. With the availability of this information, the probability of unanticipated failures can be established and the safety of the engine structure ascertained.



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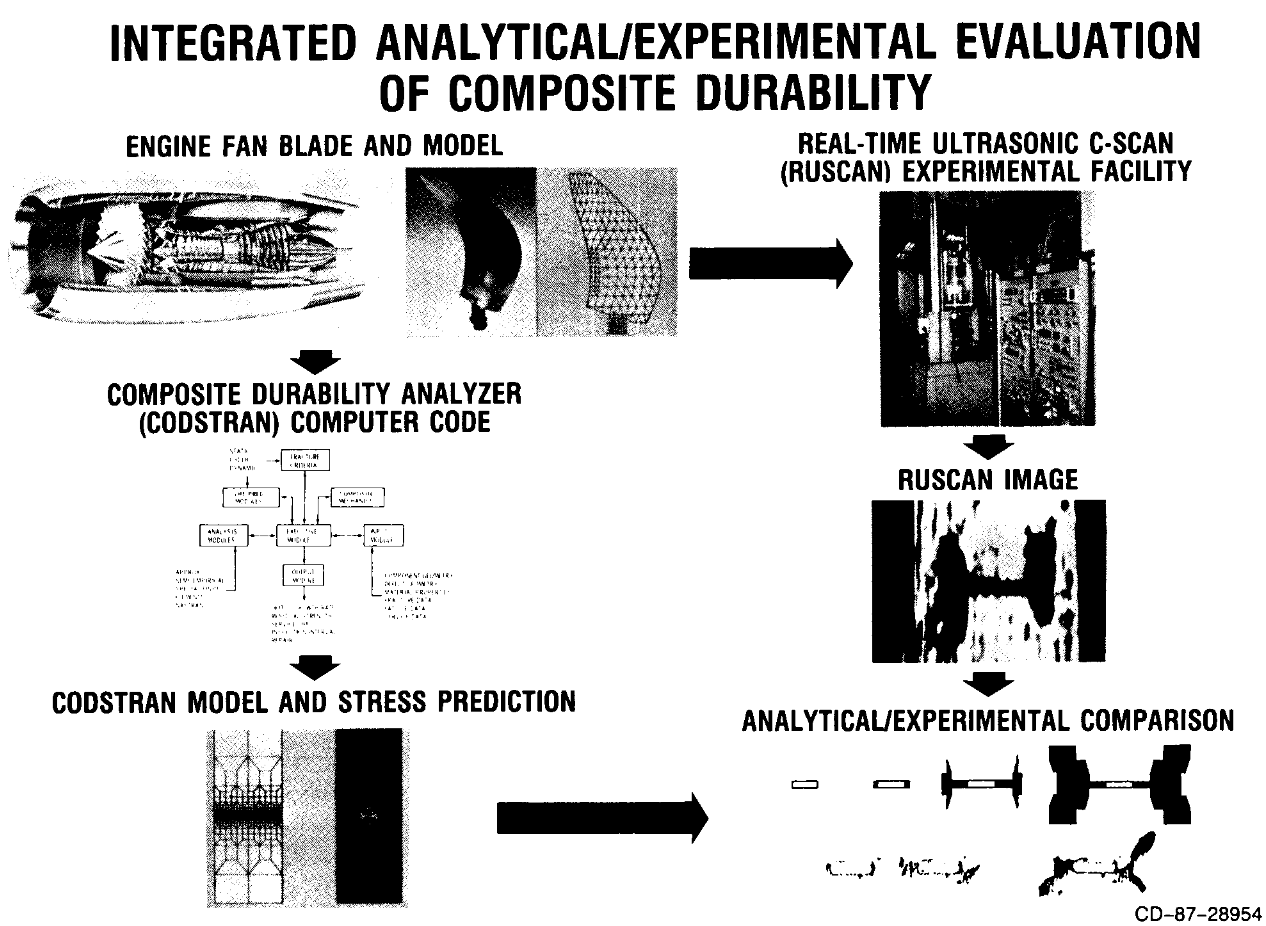
INTEGRATED ANALYTICAL/EXPERIMENTAL EVALUATION OF COMPOSITE DURABILITY

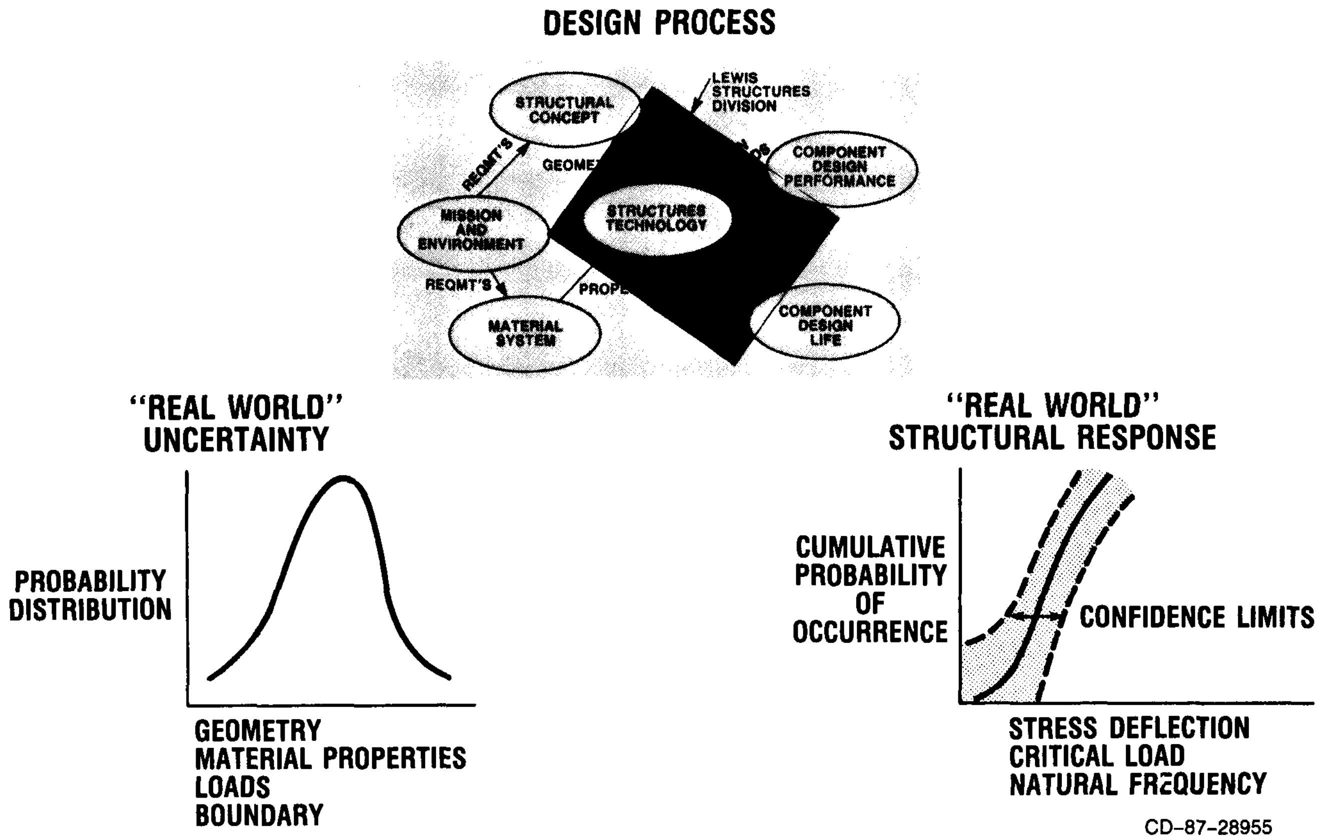
In an effort to characterize durability and damage tolerance of composite structures, an integrated research program is ongoing involving analytical methods development and experimental verification. The analytical methods including composite mechanics, composite failure theories, and cumulative damage models are incorporated into the Composite Durability Structural Analyzer finite element computer code, which assesses durability in terms of defect growth/damage progression on a ply-by-ply basis through an incremental solution scheme. The companion experimental program is conducted using the unique Real-Time Ultrasonic C-Scan Facility where sequential graphic images are created from acoustic emissions taken of a specimen in real time as it is incrementally loaded to fracture. The excellent correlation achieved between the analytical predictions and experimental observations enhances confidence in the ability to analytically assess durability of composite structures.



PROBABILISTIC STRUCTURAL ANALYSIS/DESIGN METHODOLOGY

The ingredients to a structural design - i.e., geometry, material properties, boundary conditions, and loads - are "known" only with some uncertainty. Although "risk" necessarily accompanies this uncertainty, an assessment of the degree of risk associated with a design is usually not determined. Rather, the traditional approach is to rely on deterministic design methodology and incorporate some sort of "safety factor" in an attempt to simply avoid any risk. Reducing risk in a design increases safety and reliability but at the same time increases cost. In the interest of both safety and economy, it is desirable to quantify the level of risk in a design, and probabilistic methodology provides the means to accomplish this.

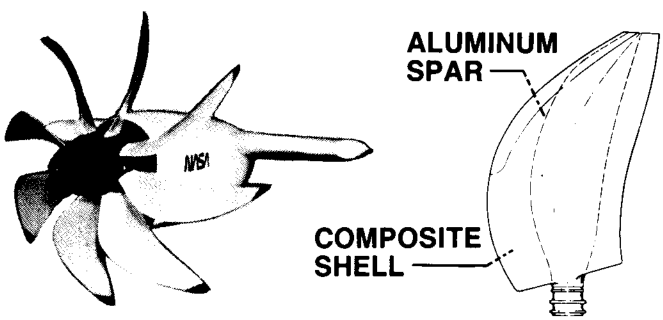
PROBABILISTIC STRUCTURAL ANALYSIS/DESIGN METHODOLOGY



STRUCTURAL TAILORING OF ADVANCED TURBOPROP BLADES

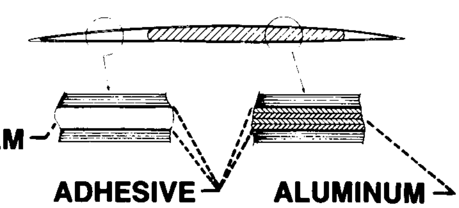
The traditional approach to propellor design would be to satisfy requirements on aerodynamic performance and structural integrity independently through numerous manual design iterations. This process, often conducted by different designers or even groups of designers, is time consuming, cumbersome, and subjective. As a result, the process is usually carried out only to the point where a satisfactory design, but not likely the "best'' design, is achieved. The Structural Tailoring of Advanced Turboprops computer code was developed to streamline, automate, and formalize the turboprop design process by incorporating multidisciplinary analysis methodology (aerodynamic, acoustic, and structural) together with numerical optimization techniques into a computationally effective design system. The system has demonstrated its utility in successful optimizations of large-scale, advanced propfan designs to achieve reductions of several percent in aircraft direct operating cost.

STRUCTURAL TAILORING OF ADVANCED TURBOPROPS (STAT)



TURBOPROP STAGE AND PROPELLER

BLADE INTERNAL STRUCTURE



MULTIDISCIPLINARY ANALYSIS MODULES

- ADS OPTIMIZER
- BLADE MODEL GENERATION
- AERODYNAMIC ANALYSIS
- ACOUSTIC ANALYSIS
- STRESS AND VIBRATIONS ANALYSIS
- FLUTTER ANALYSIS
- 1 P FORCED REPONSE

TYPICAL ANALYSIS RESULTS

	INITIAL	FINAL
EFFICIENCY, %	82.86	83.17
NEAR-FIELD NOISE, DB	143.8	137.3
WEIGHT, LB	41.1	41.2
DOC	−.853	−4.201

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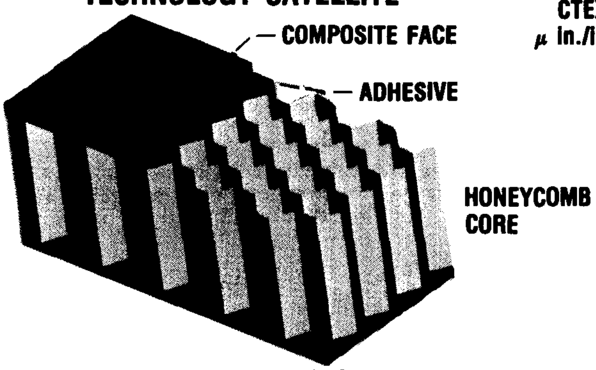
COMPOSITE SANDWICH STRUCTURAL SIMULATION FOR SATELLITE ANTENNA REFLECTORS

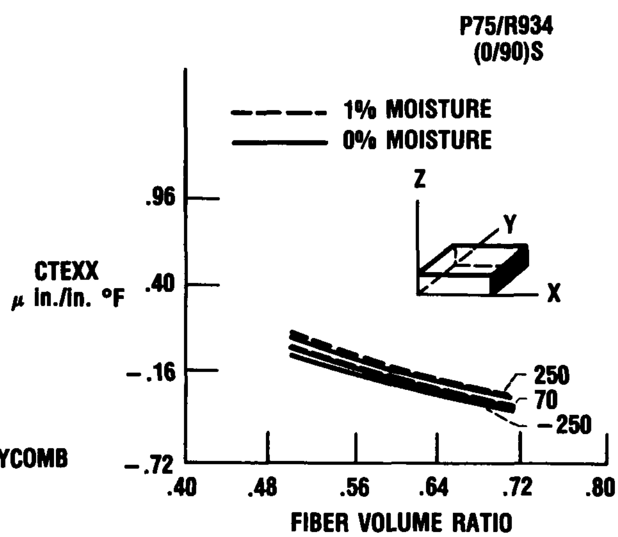
A recent enhancement of the Integrated Composites Analyzer computer code has extended its applicability to composite sandwich configurations. The new feature was successfully demonstrated in the preliminary design of the composite antenna reflector structure for the Advanced Communications Technology Satellite. In this application, parametric studies were conducted to determine acceptable face sheet and honeycomb core configurations necessary to provide a thermal distortion-free structure in a simulated space environment. The simplified, approximate methodology developed to model sandwich composite structures has been verified using detailed 3-D finite element analysis.

COMPOSITE SANDWICH STRUCTURAL SIMULATION FOR ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE ANTENNA REFLECTORS

ACTS ADVANCED COMMUNICATION TECHNOLOGY SATELLITE



COMPUTER-GENERATED MODEL OF THE STRUCTURE USED FOR THE ANALYSIS



COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF FVR AND HYGROTHERMAL CONDITIONS

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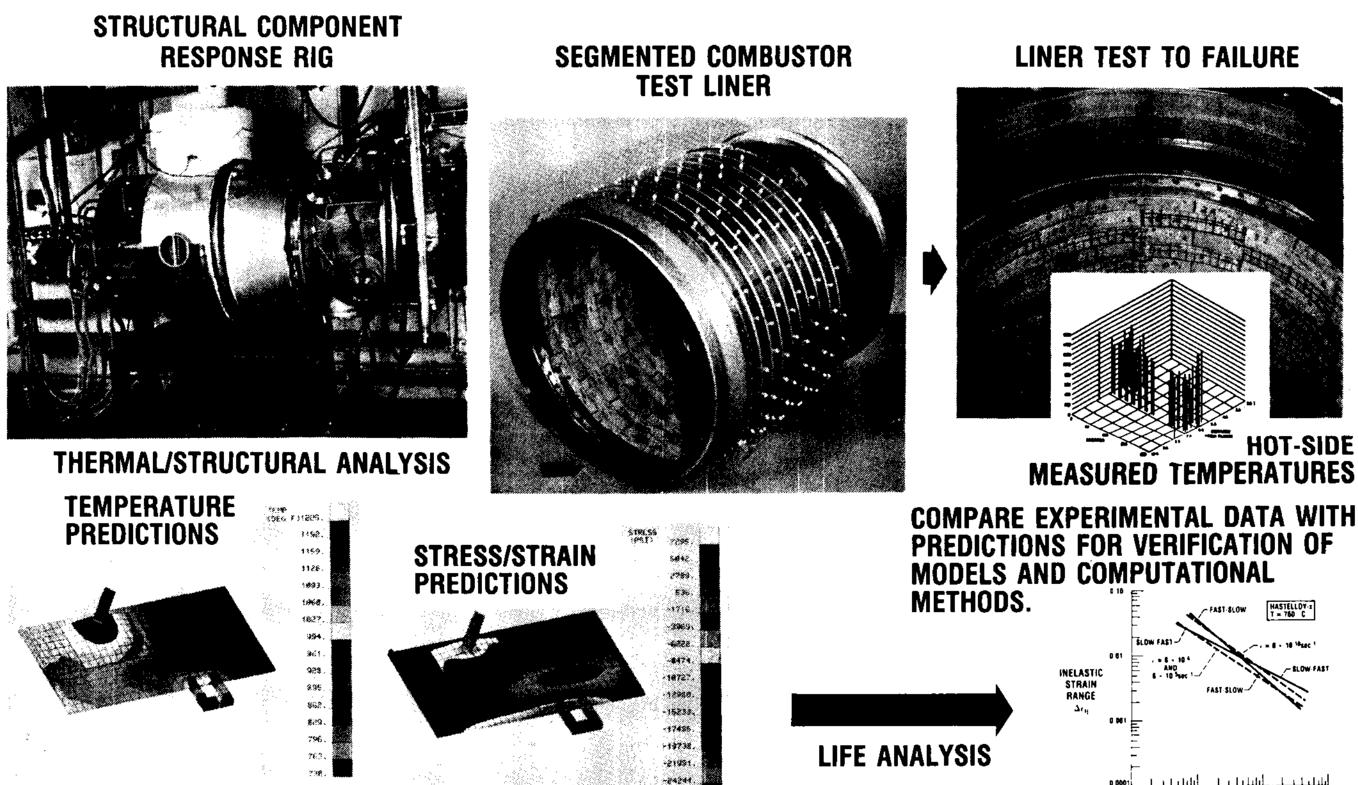
ADVANCED COMBUSTOR LINER STRUCTURAL CONCEPT
TESTING AND THERMAL/STRUCTURAL/LIFE ANALYSIS

Advanced combustor liner structural concepts and materials are being tested and analyzed as part of a cooperative research program between NASA Lewis Research Center and Pratt & Whitney Aircraft. The integrated and interdisciplinary test/analysis program is conducted for advanced "floatwall" or panelled combustor liner segments. The cyclic tests, conducted in the Structural Component Response Rig, simulate the taxi, ascent, cruise, and descent temperature transients of an engine flight profile using a computer-controlled quartz lamp heating system. High-quality data bases of liner temperatures and distortions are obtained for calibration and verification of analytical models and computational tools used for predicting the structural response and life of representative liners.

INTEGRATED TEST AND THERMAL/STRUCTURAL/LIFE ANALYSIS OF AN ADVANCED COMBUSTOR STRUCTURAL CONCEPT



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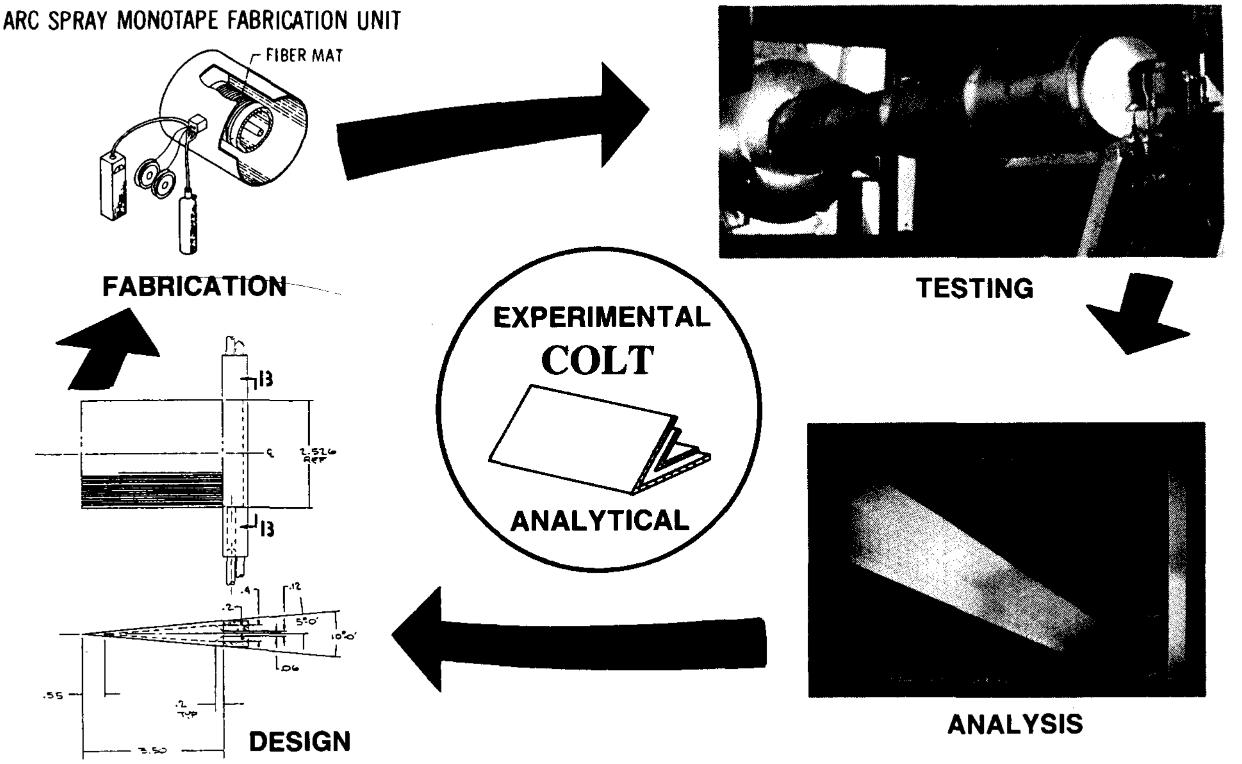
METHODOLOGY OF LEADING EDGE CONCEPT EVALUATION

Leading edges on hypersonic aircraft are subjected to high heat flux loads induced by aerodynamic friction. To accommodate this requires advanced high-temperature materials and structural cooling. To address this, the Cowl Lip Technology Program is underway to evaluate materials and actively cooled leading-edge concepts. The problem is approached through an integrated program of design, analysis, fabrication, and testing. Leading edge concepts are designed and representative test articles are fabricated from candidate materials including metal- and ceramic-matrix composites. The articles are tested in a high heat flux facility to obtain experimental data for comparison with analytical predictions. The data and analytical predictions provide the basis for assessing the design concept.

METHODOLOGY OF LEADING EDGE CONCEPT EVALUATION



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16. Abstract

Aeropropulsion systems present unique problems to the structural engineer. The extremes in operating temperatures, rotational effects, and behaviors of advanced material systems combine into complexities that require advances in many scientific disciplines involved in structural analysis and design procedures. This session provides an overview of the complexities of aeropropulsion structures and the theoretical, computational, and experimental research conducted to achieve the needed advances.

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